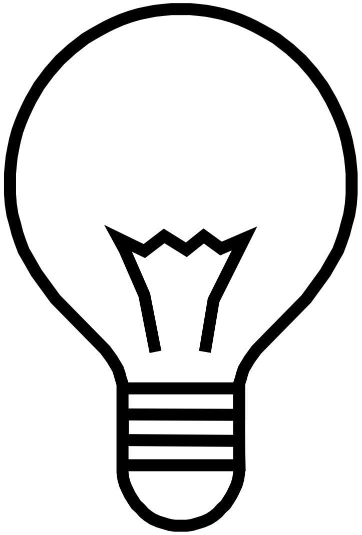
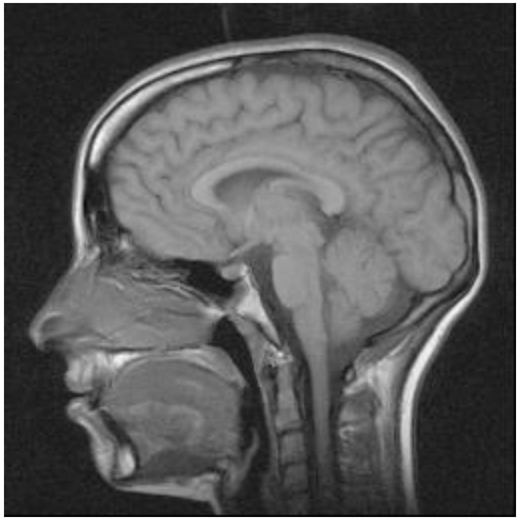
Oxford School on Neutron Scattering

Neutron imaging

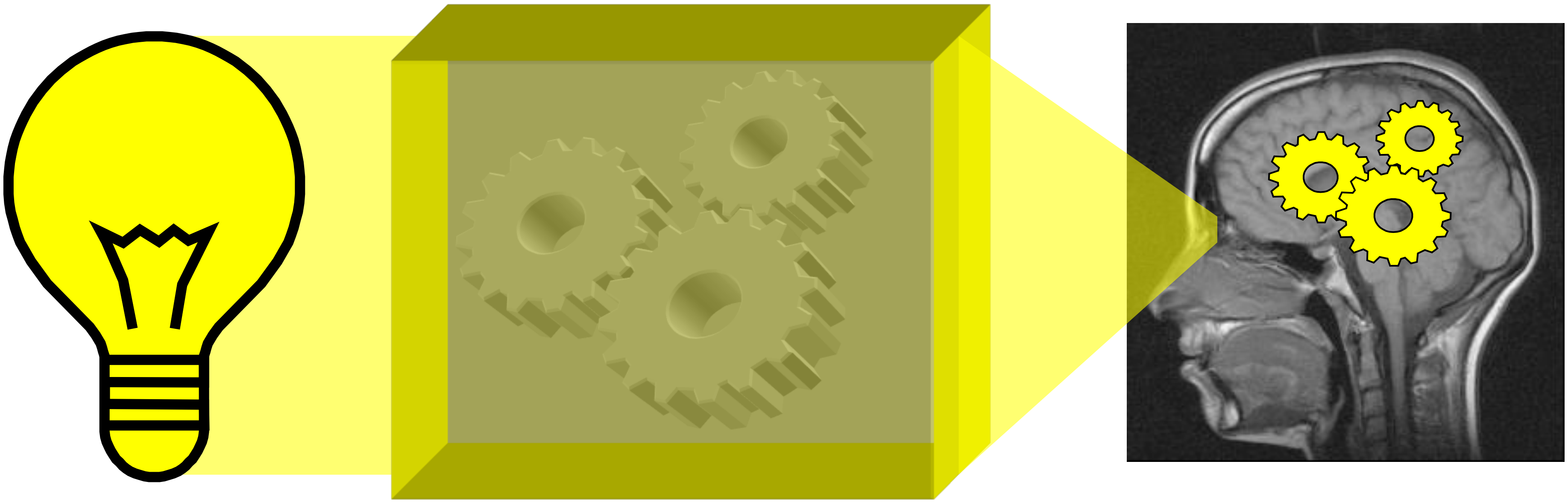
Nikolay Kardjilov

Neutron imaging

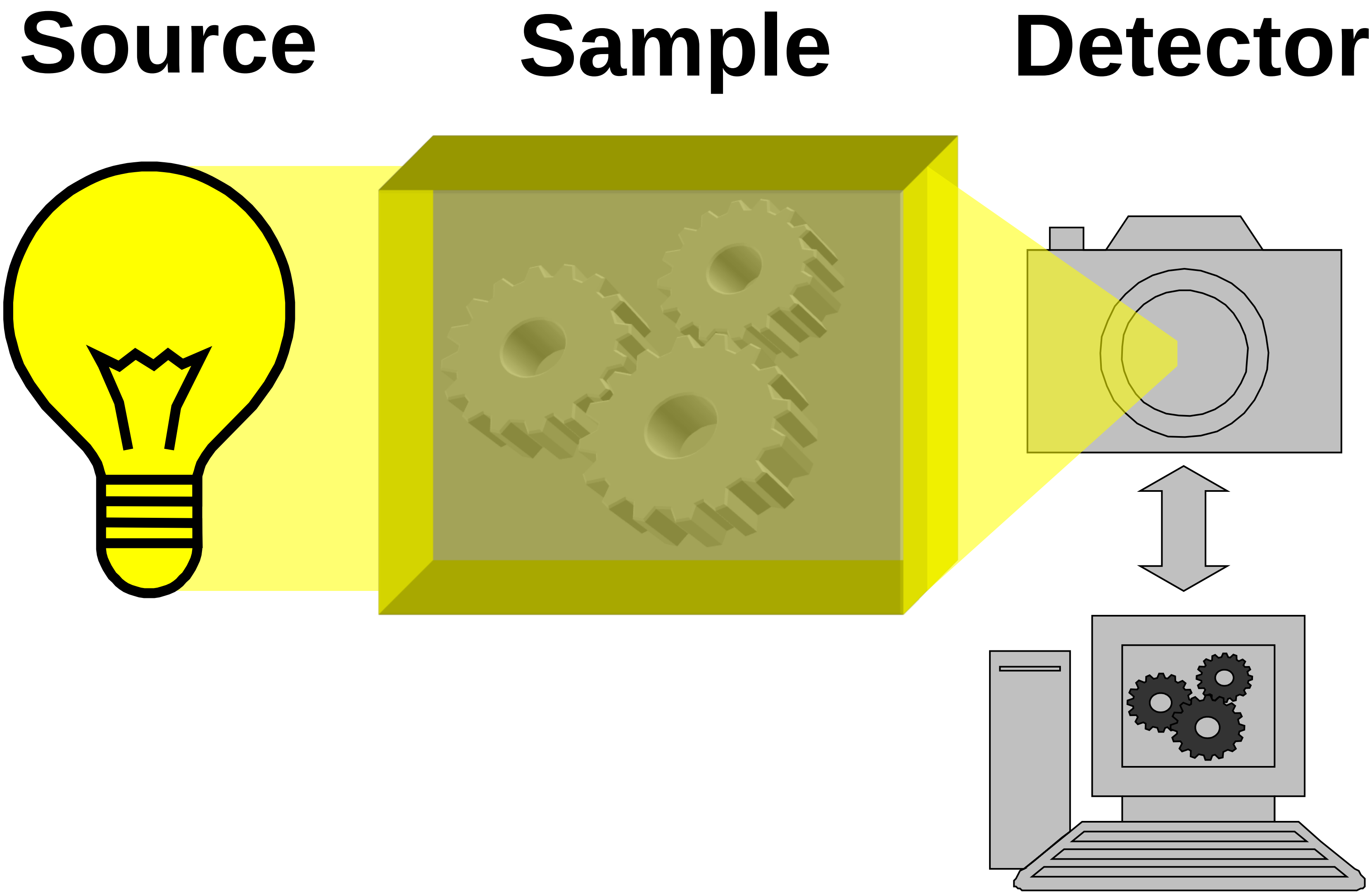




Neutron imaging



Neutron imaging



Introduction

One of the first X-ray experiments late in 1895 performed by Konrad Röntgen was a film of a hand.

The bones and also finger rings deliver much higher contrast than the soft tissue.

Introduction

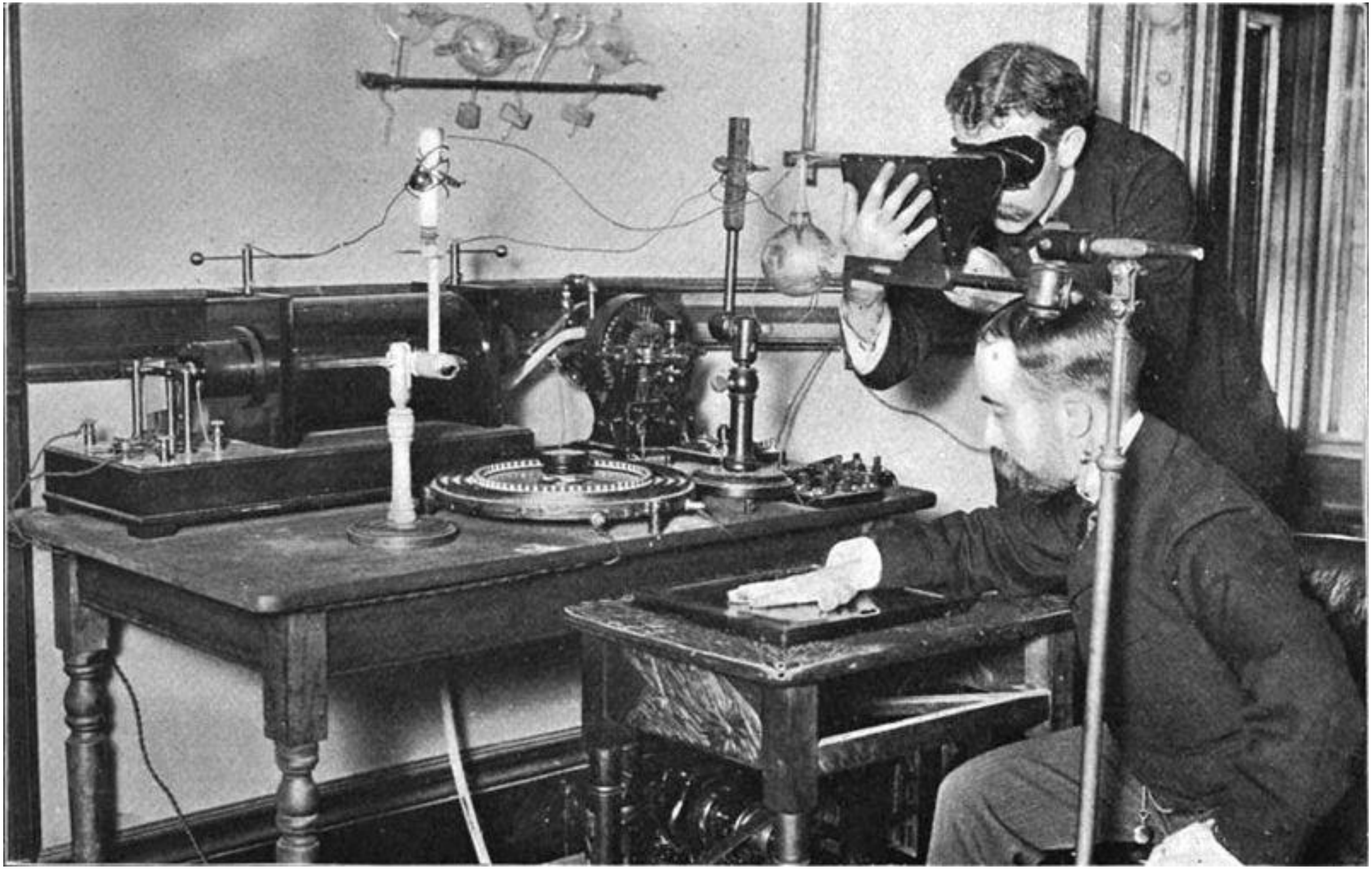
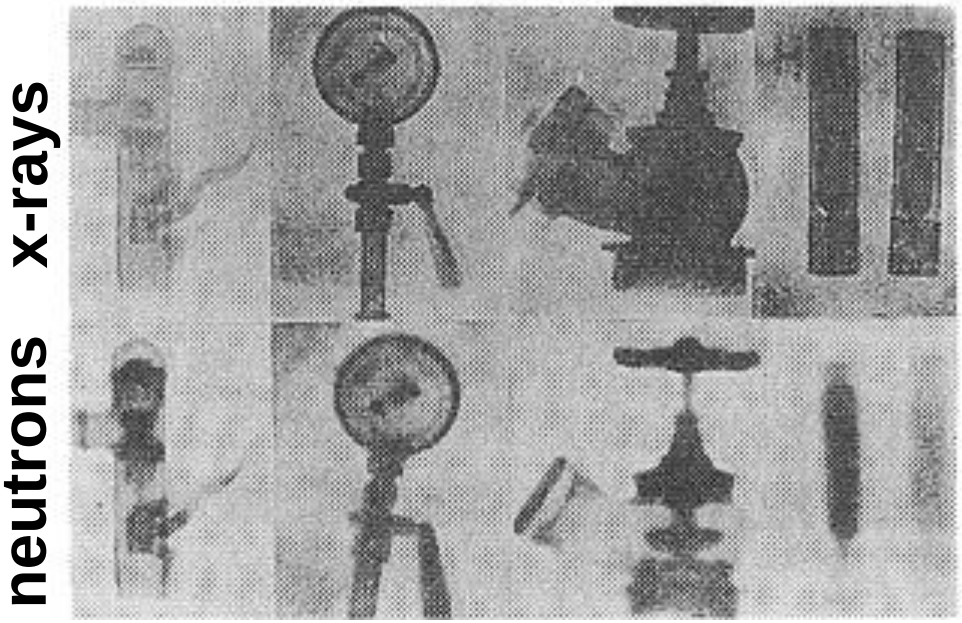


Photo of experimenters taking an X-ray with an early Crookes tube apparatus, from the late 1800s.

Roots of neutron radiography

Comparison between x-ray and neutron images



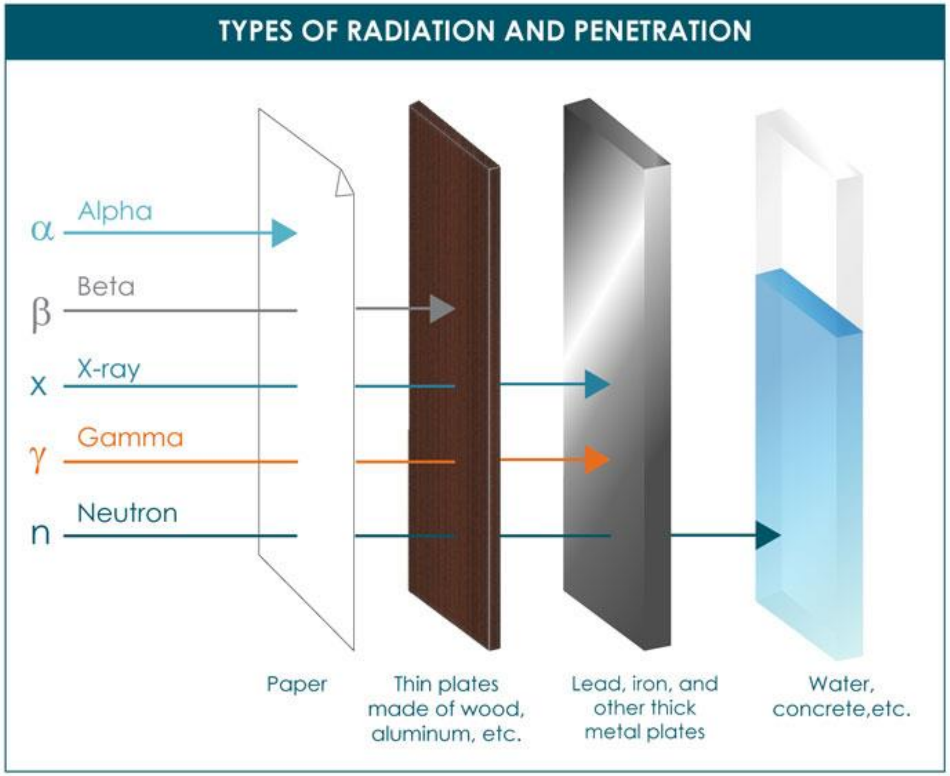
Berlin, 1935 – 1938
H. Kallmann & Kuhn with Ra-Be and neutron generator

Berlin until Dec. 1944
O. Peter with an accelerator neutron source

But the real programs with neutrons started after World War II at research reactors

Physical Background

- Free neutrons are able to penetrate matter of relevant thickness (several µm to dm)



https://www.mirion.com/learning-center/radiation-safety-basics/types-of-ionizing-radiation

Interaction principle of neutrons with matter

- Neutrons interact with the **nuclei** of the atoms only

- The probability for interaction with matter is expressed by *„microscopic cross-sections“* – **σ** , the unit is „barn = 10^{-24} cm^2“

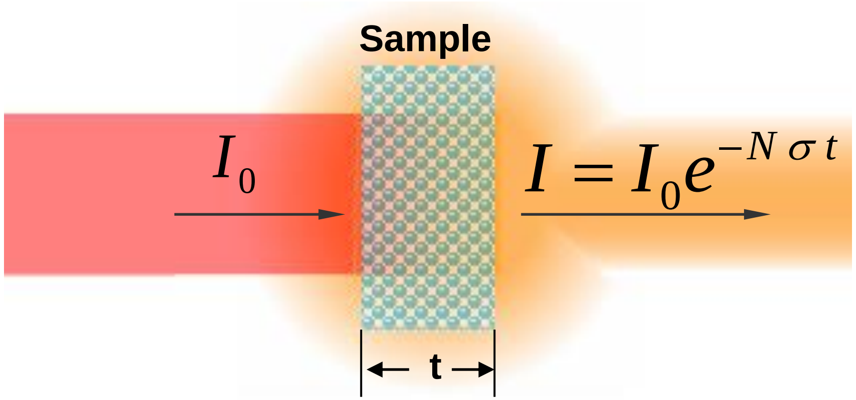
- For each type of interaction a microscopic cross-section can be defined: $\boldsymbol{\sigma_{absorption}}$, $\boldsymbol{\sigma_{scattering}}$, $\boldsymbol{\sigma_{total} = \sigma_{abs.} + \sigma_{scatt.}}$

- The *“macroscopic cross-section”* Σ, also called *“attenuation coefficient”* is defined as : $\boldsymbol{\Sigma = N^* \sigma_{tot}}$, the unit is cm^{-1}

- N = nuclear density = **(ρ*A)/M** (A=Avogadro‘s number, M=mass)

- $\boldsymbol{\Sigma = N^* \sigma_{tot} = \sigma_{tot}{}^*(\rho^*A)/M \rightarrow \Sigma \sim \rho}$

Attenuation in transmission mode



- N – numerical density of sample atoms per cm^3
- I_0 - incident neutrons per second per cm^2
- σ - neutron cross section in ~ 10^{-24} cm^2
- t - sample thickness

Transmission (Beer-Lambert's law)

$$T = \frac{I}{I_0} = e^{-\Sigma * d} = e^{-\sigma * \frac{A}{M} * \rho}$$

and inverted …

$$\Sigma * d = \ln(\frac{I_0}{I})$$

Thickness d can be obtained when Σ is known

Density or composition derived if thickness d is known

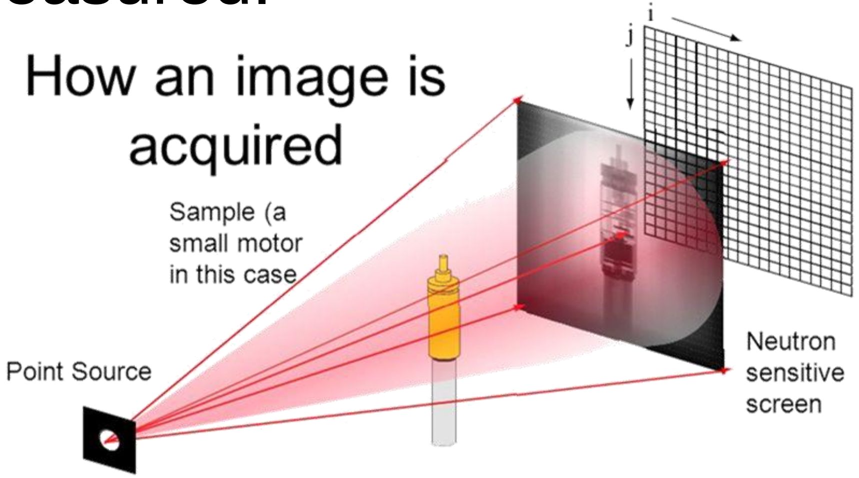
https://www.psi.ch/en/niag/neutron-interaction-with-matter

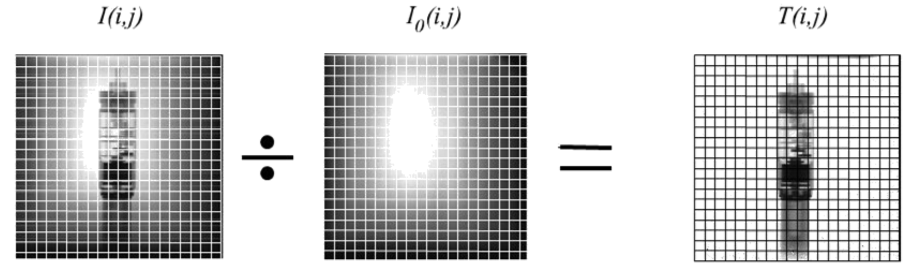
Physical Background

- Neutrons can be detected with suitable devices (neutron imaging detectors)
- The distribution of the neutrons without a sample (unperturbed, «open» beam) I_0 and after interaction within the sample I are measured.

- The ratio of the two images gives the neutron transmission in the beam direction *T(i,j)*

$$T = \frac{I}{I_0} = e^{-\Sigma * d}$$



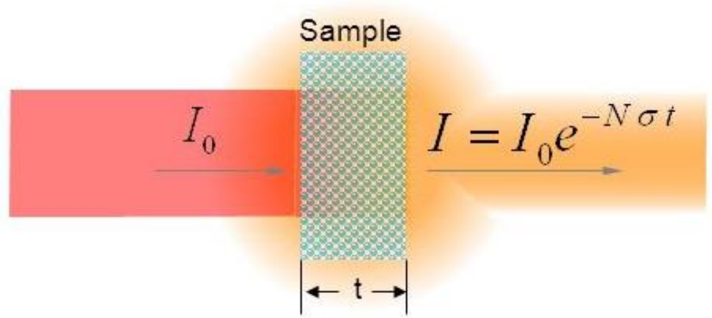


https://www.physics.nist.gov/MajResFac/NIF/radiography.html

Physical Background

- The neutron beam can penetrate matter of relevant thickness of several µm to dm.
- The transmission of neutrons through materials can be described by Beer-Lambert law.

- Contrast is due to attenuation of radiation
- Scattering density of material can be extracted
- N - density of sample atoms per cm^3
- I_0 - incident neutrons per second per cm^2
- σ - neutron cross section in ~ 10^{-24} cm^2



courtesy: Dr. David L. Jacobson (NIST)
https://slideplayer.com/slide/9149496/

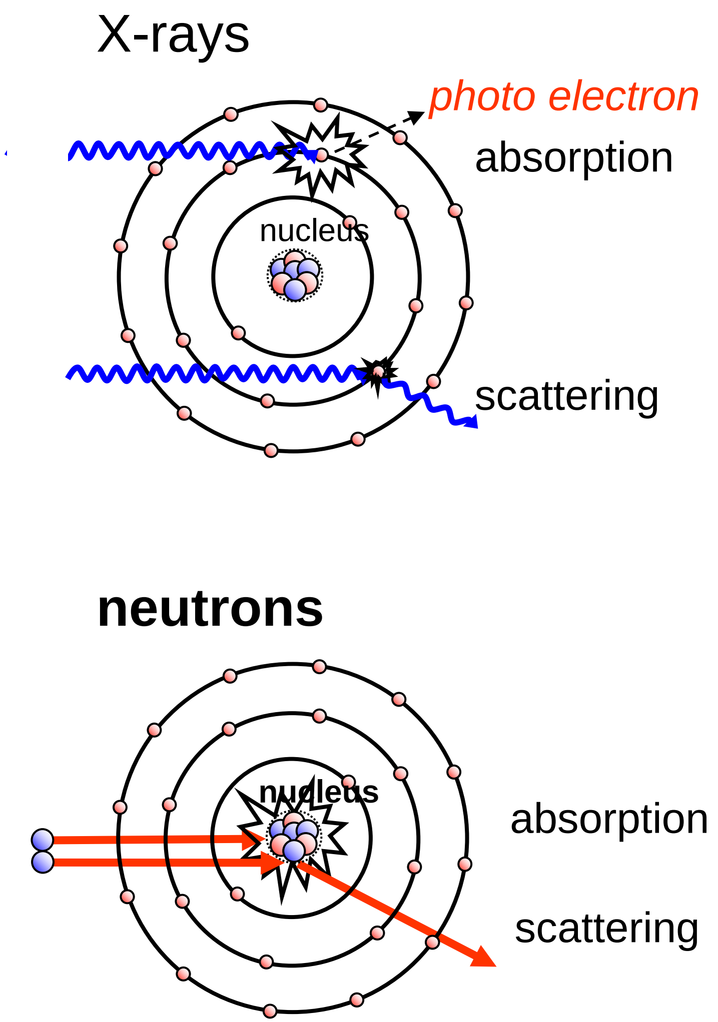
Physical Background

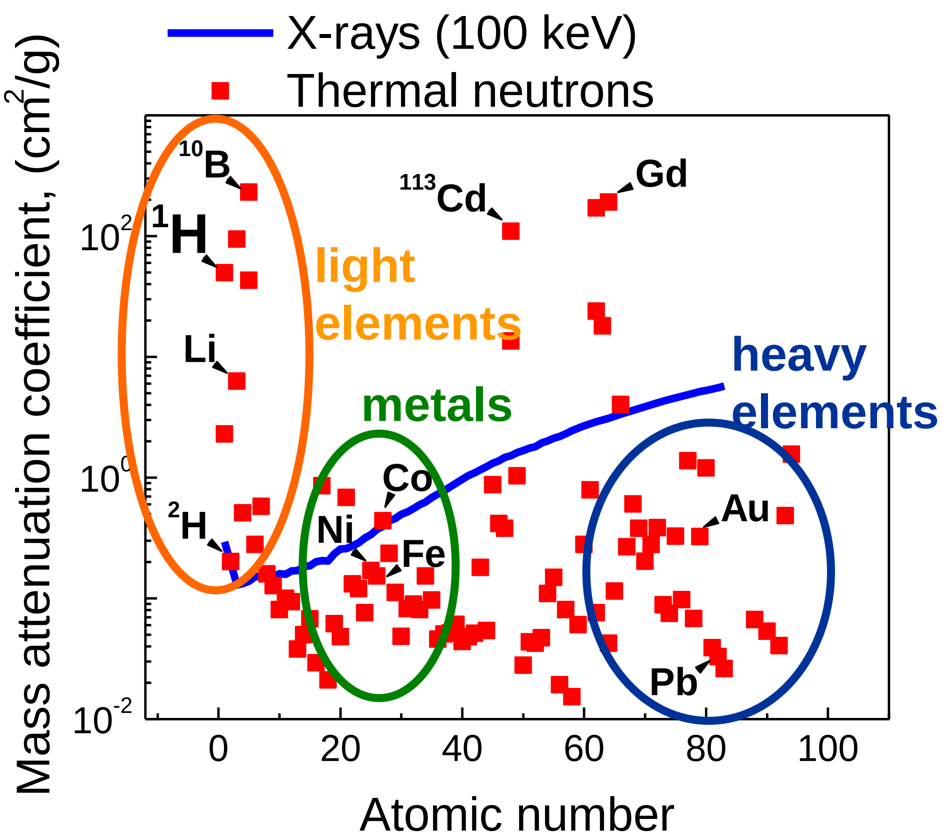
- The neutron beam can penetrate matter of relevant thickness of several µm to dm.
- The transmission of neutrons through materials can be described by Beer-Lambert law.
- The neutron transmission depends on the properties of the material and neutron energy
- Neutrons «distinguish» not only materials but also particular isotopes (e.g. $^{10}B/^{11}B$; $^{6}Li/^{7}Li$)

Basic principles & terminology

- **Neutrons** interact with the **nuclei** of the sample materials
- **X rays** only interact with the **electrons** of the atomic shell

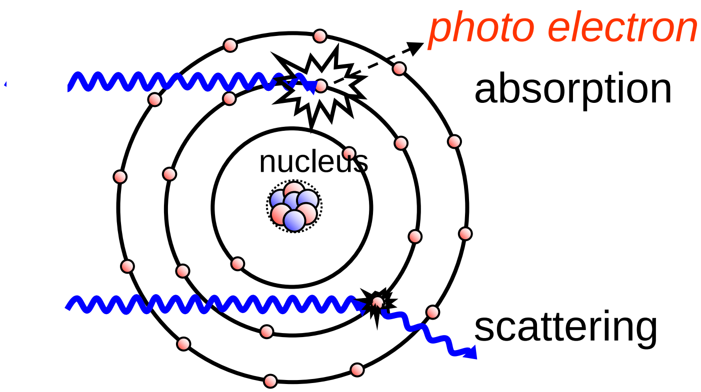
Neutron interaction with matter





Neutron interaction with matter

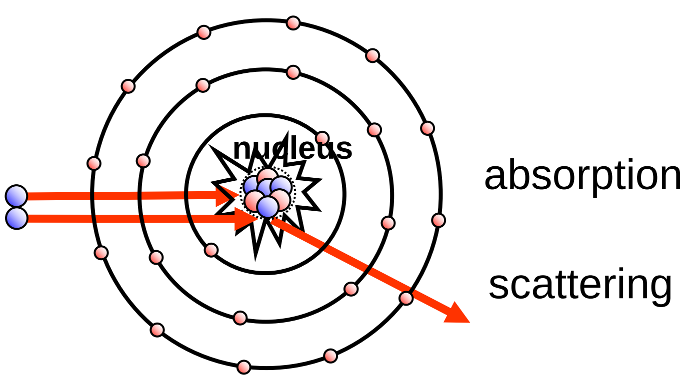
X-rays



Attenuation coefficients with X-ray [cm?^{1}]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 0.02																	He 0.02
Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
Cs 1.42	Ba 2.73	La 5.04	Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At	Rn 9.77
Fr	Ra 11.80	Ac 24.47	Rf	Ha													
Lanthanides	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07			
*Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr x-ray			

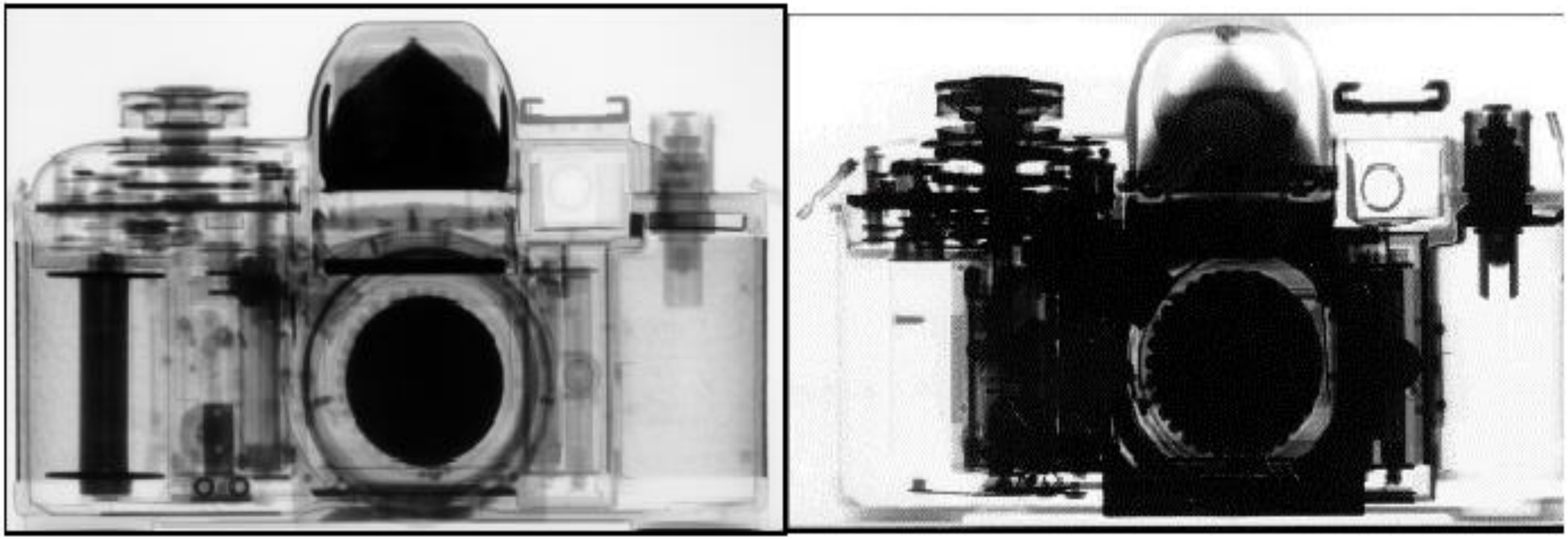
neutrons



Attenuation coefficients with neutrons [cm?^{1}]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 3.44																	He 0.02
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po	At	Rn
Fr	Ra 0.34	Ac	Rf	Ha													
*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75			
**Actinides	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm	Bk	Cf	Es	Fm	Md	No	Lr neut.			

Neutron radiography - examples



The example for a camera helps to explain differences in neutron (left) and X-ray (right) radiography. Whereas the hydrogen containing parts can be visualised with neutron even at thin layers, thicker metallic components are hard to penetrate with X-rays.

Images courtesy: Dr. Eberhard Lehmann (Paul-Scherrer-Institute, Switzerland)

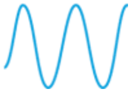
Resolution

- Beam optimisation
- Detector development

Contrast

- Neutron interaction with matter

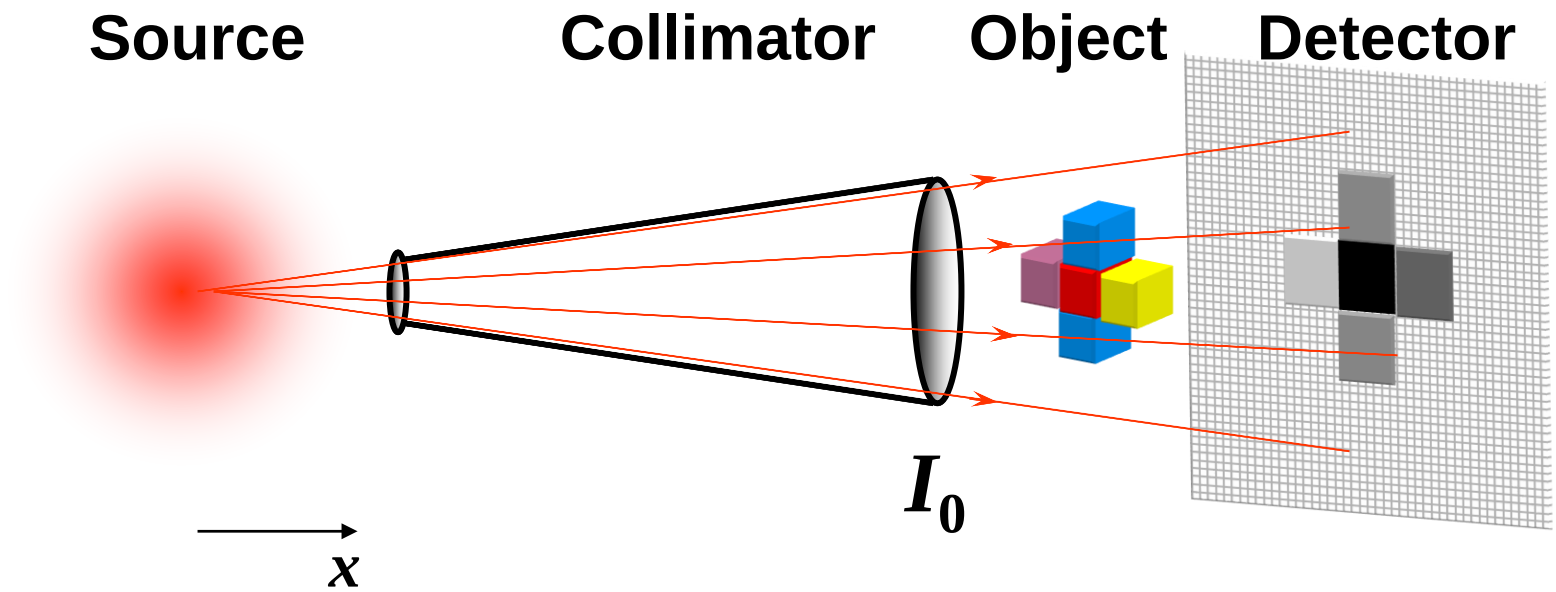
- absorption



- scattering

- magnetic interaction

Beam optimisation



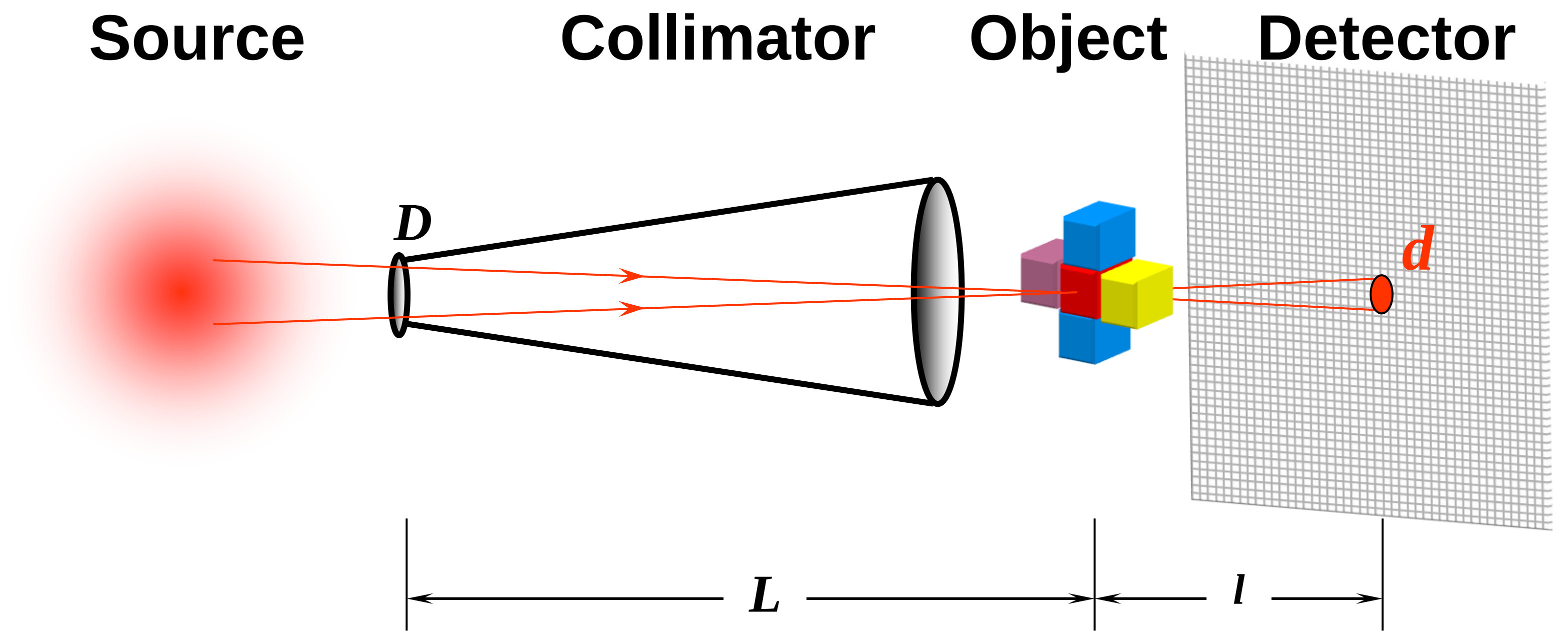
$$\sim I_0 e^{-\int \Sigma(x)dx}$$

x – propagation direction

I_0 – primary beam

$\Sigma(x)$ – attenuation coefficient

Beam optimisation



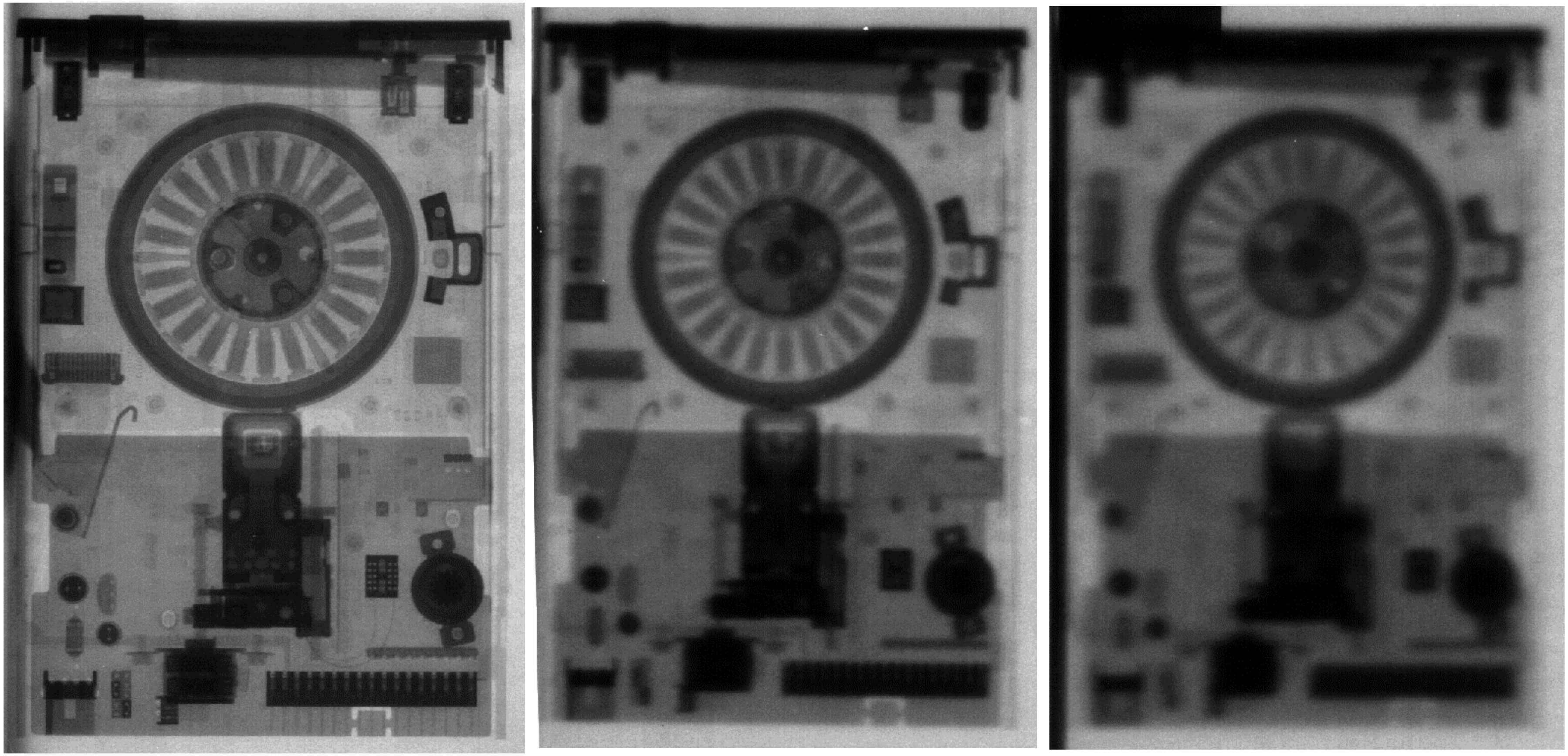
D – Collimator aperture

L – Distance Collimator-Object

l – Distance Object-Detector

$$d = \frac{l}{L/D}$$

Neutron imaging

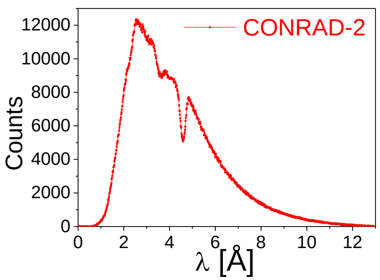


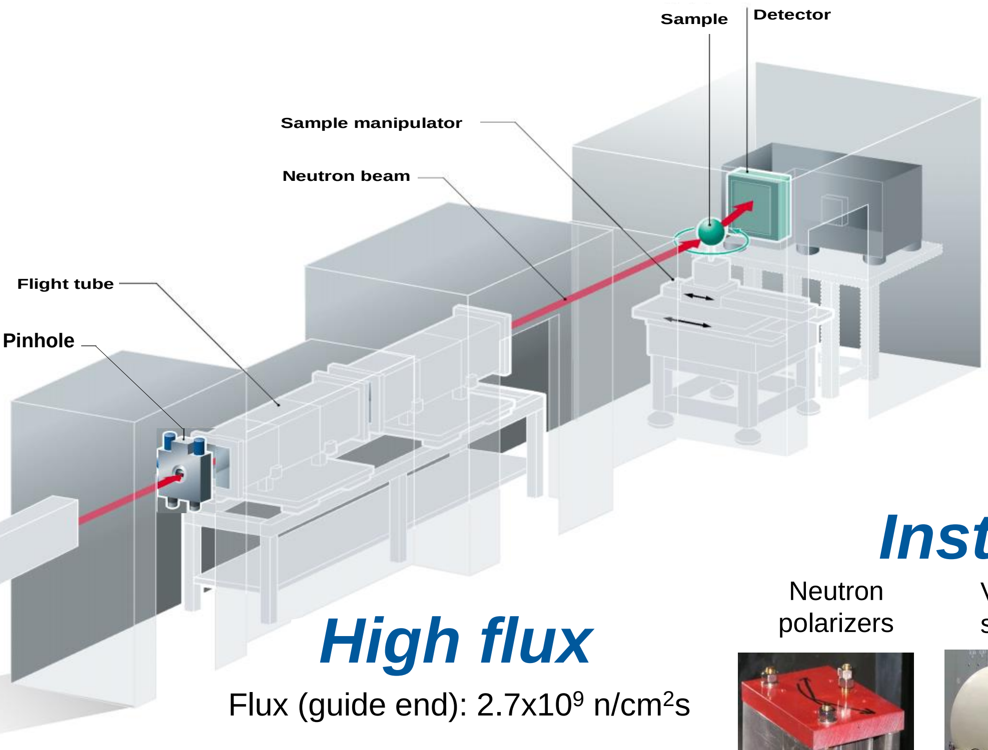
Radiographs of a 3,5'' floppy drive in 0 cm, 10 cm and 20 cm distance from a film + Gd sandwich taken at a cold neutron guide with *L/D*=71.

B. Schillinger, Estimation and measurement of L/D on a cold and thermal neutron guide, in: Nondestructive Testing and Evaluation, World Conference on Neutron Radiography, vol. 16, Osaka, 1999, pp. 141–150

Cold neutrons

Wavelength range: 1.5 Å – 10 Å





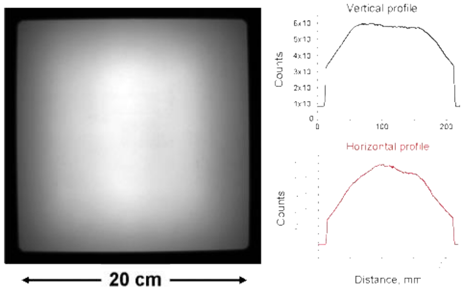
Guide system: super-mirror coated neutron guide (M=3) with a curvature of 750 m and length of 15 m followed by linear guide section (M=2) with a length of 10 m.

High flux

Flux (guide end): 2.7x10^9 n/cm^{2}s

Large beam

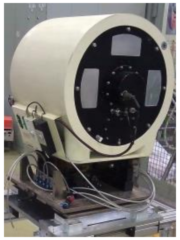
Beam size: 20 cm x 20 cm



Instrumentation

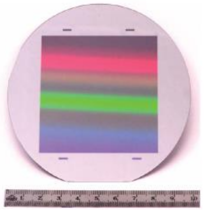
Neutron polarizers

Velocity selector

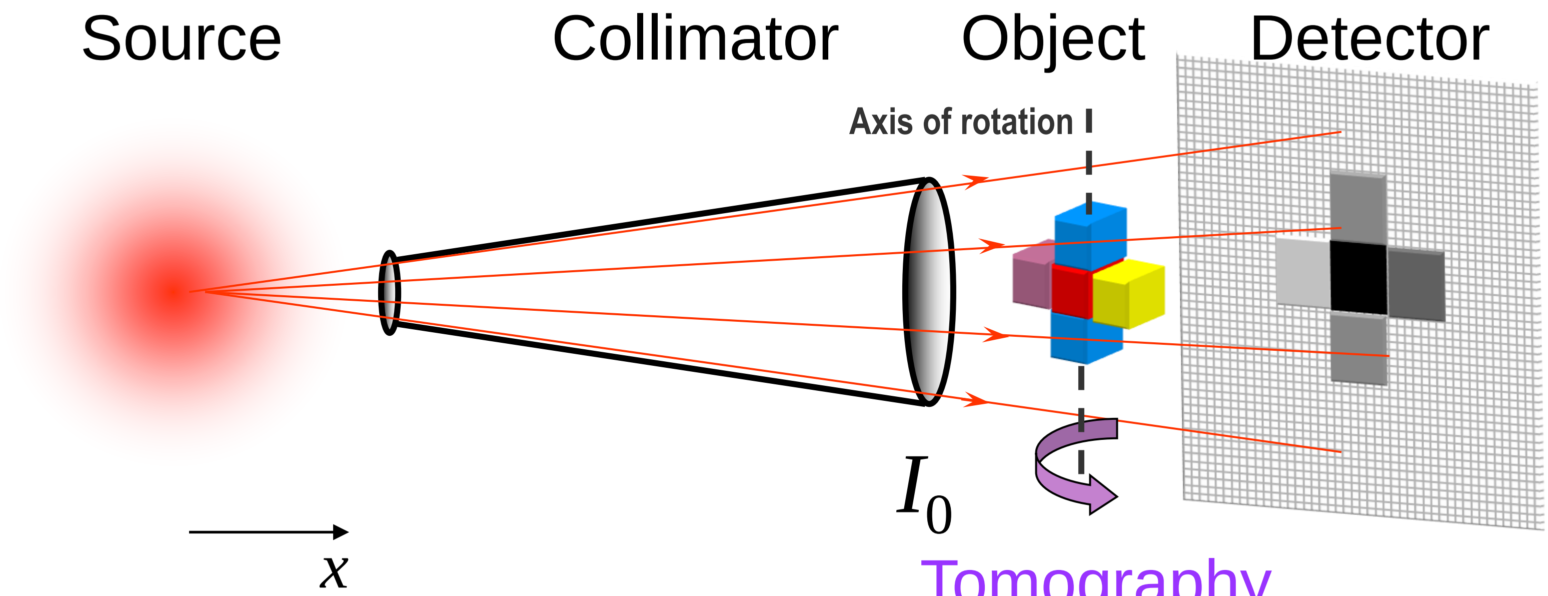


Double-crystal monochromator

Grating interferometry



Tomography



Tomography

$$\sim I_0 e^{-\int \Sigma(x)dx}$$

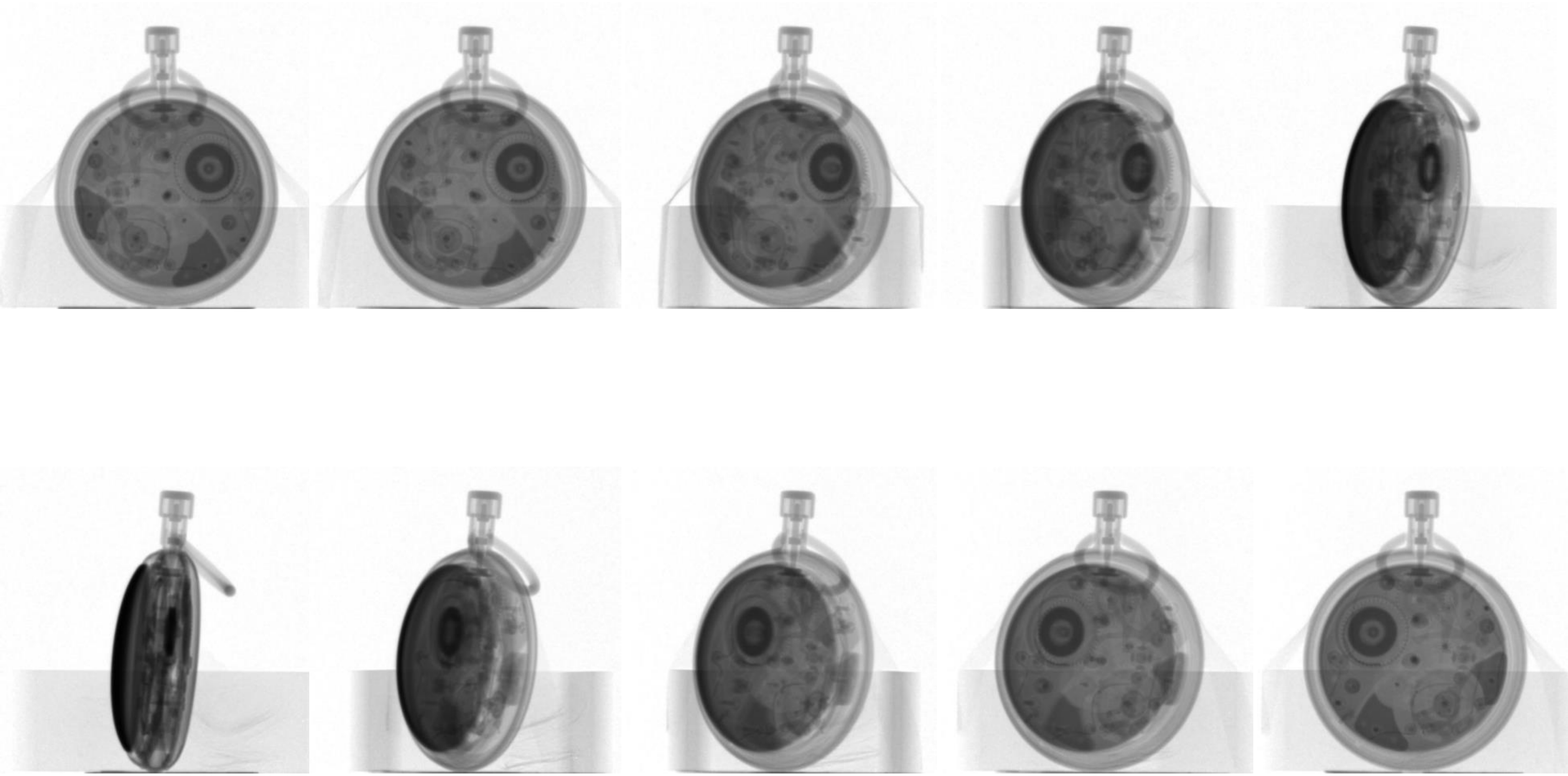
x – propagation direction

I_0 – primary beam

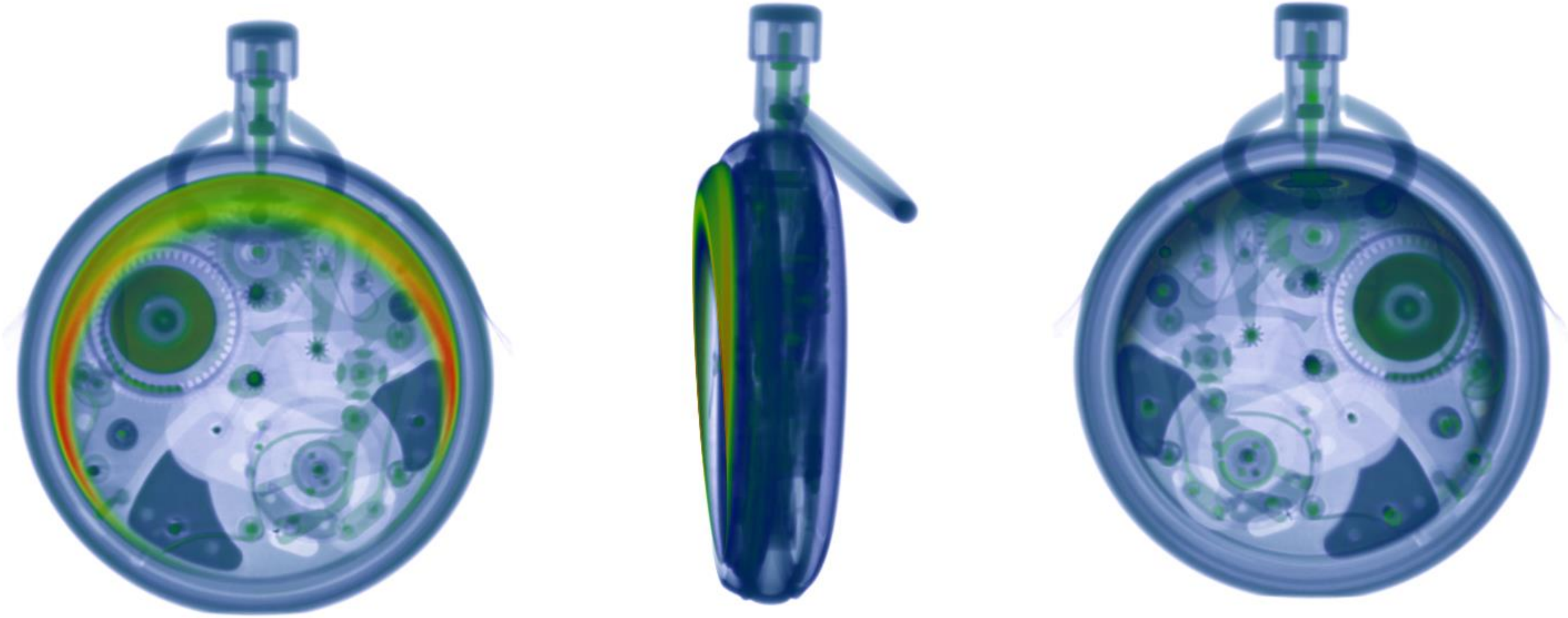
$\Sigma(x)$ – attenuation coefficient

Neutron imaging

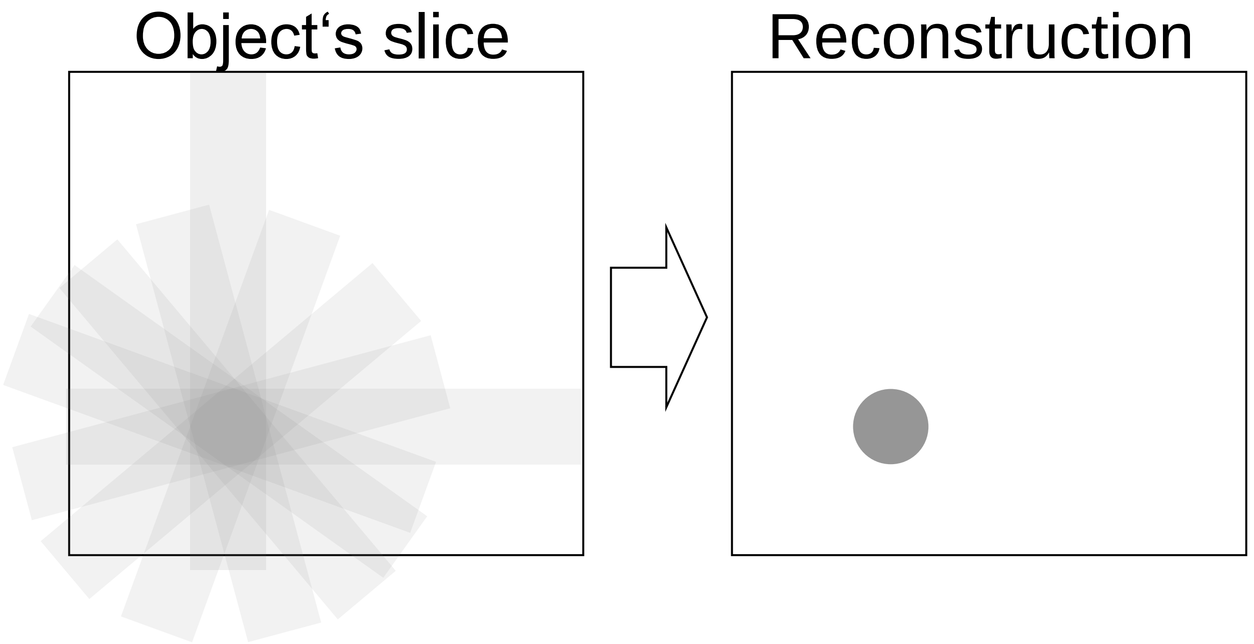
Single tomographic projections



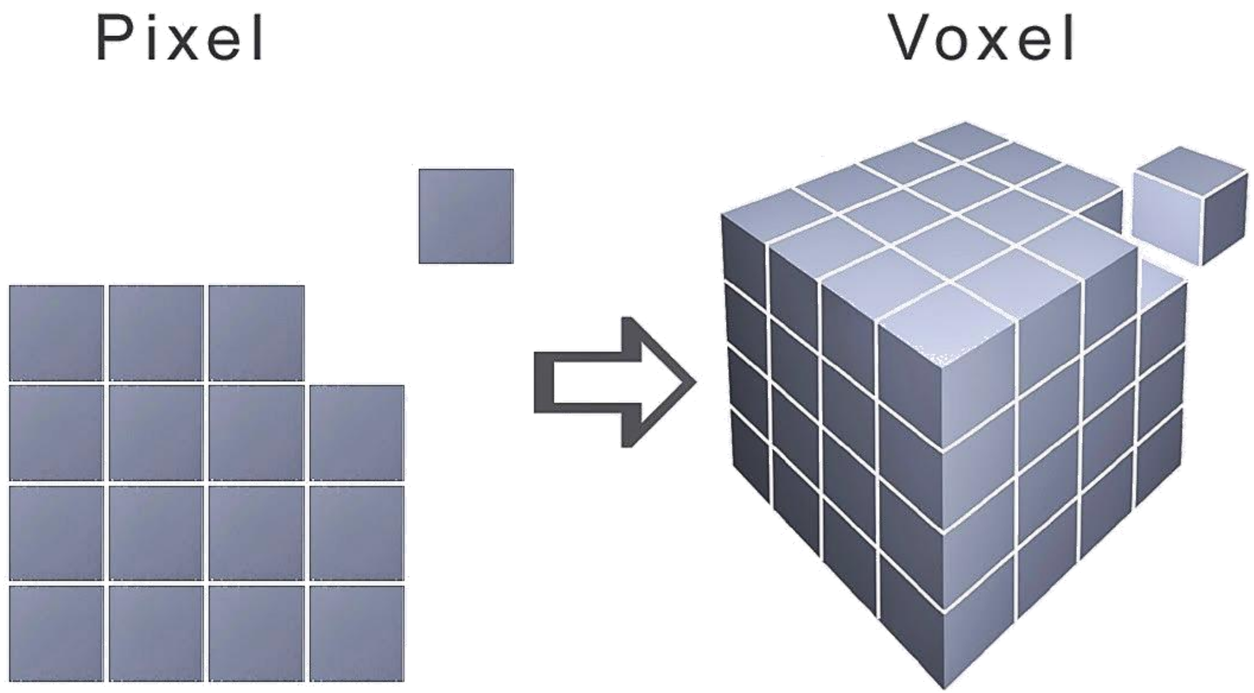
Tomographic reconstruction



Backprojection



Tomography



Radiography
(2D image of the transmission~$e^{-\Sigma d}$)

Tomography
(3D matrix of the attenuation coefficients Σ)

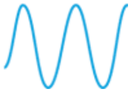
Resolution

- Beam optimisation
- Detector development

Contrast

- Neutron interaction with matter

- absorption



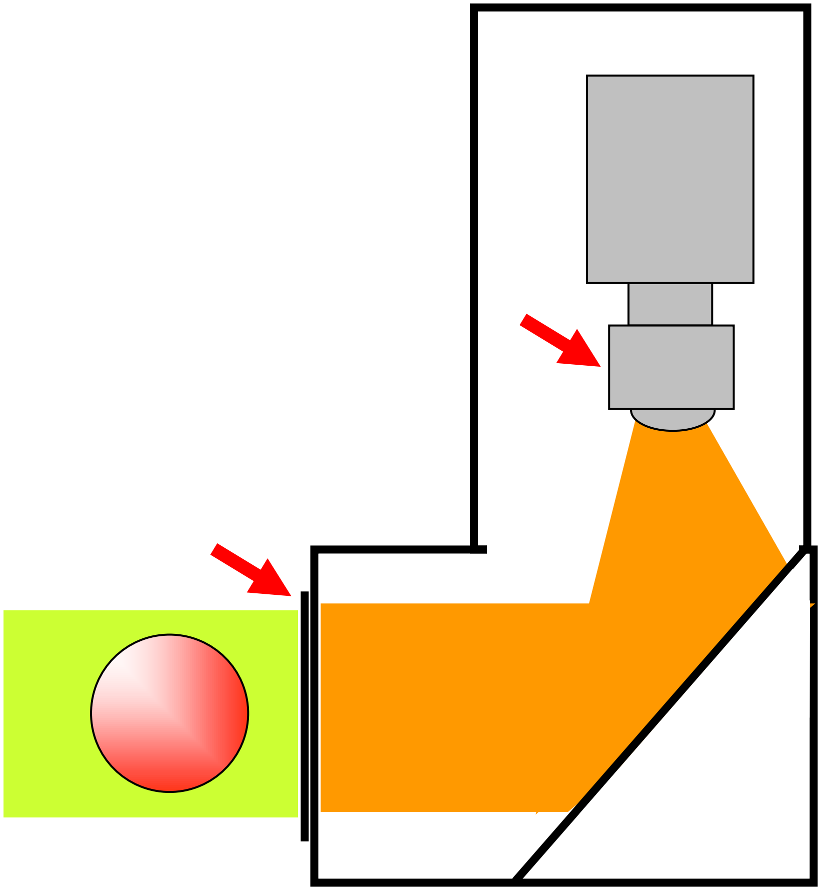
- scattering

- magnetic interaction

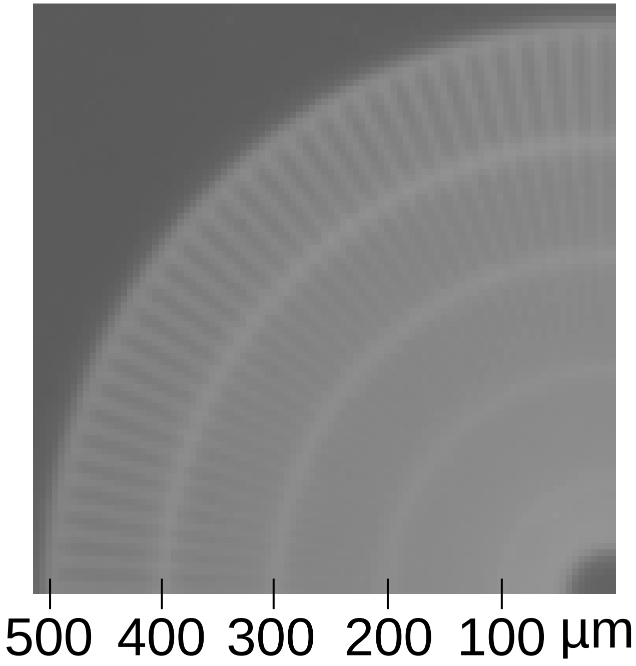
Detector development

Standard setup

Detector system

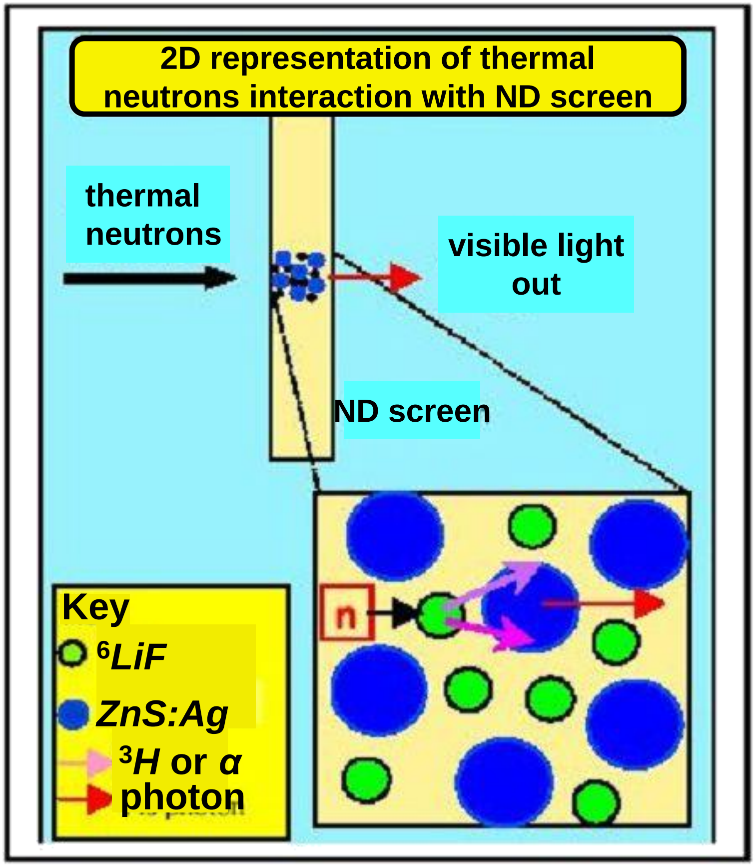


Scintillator: 200 µm 6LiF
Lens system: 50 mm
Pixel size: 100 µm
Exposure time: 20 s



Detector development

The ZnS+^{6}LiF scintillation screen is the limit of resolution.



The reaction products of

^{6}Li(n,α) ->^{3}H + ^{4}He + 4.7 MeV

have to be stopped in the ZnS scintillation screen.
Their average range is in the order of 50-80 μm.

About 177,000 photons are generated per detected neutron.

With thinned scintillation screens, we can achieve resolution in the order of 20-30 μm.

Slide courtesy: Dr. Burkhard Schillinger (FRM-II, Munich, Germany)

Capture reactions for thermal / cold neutrons

$^{3}He + {}^{1}n \Rightarrow {}^{3}He + {}^{1}p + 0.77\ MeV$

→ $^{6}Li + {}^{1}n \Rightarrow {}^{3}H + {}^{4}He + 4.79\ MeV$

$^{10}B + {}^{1}n \Rightarrow {}^{7}Li + {}^{4}He + 2.78\ MeV$ (7%)

$\Rightarrow {}^{7}Li^{*} + {}^{4}He + 2.30\ MeV$ (93%)

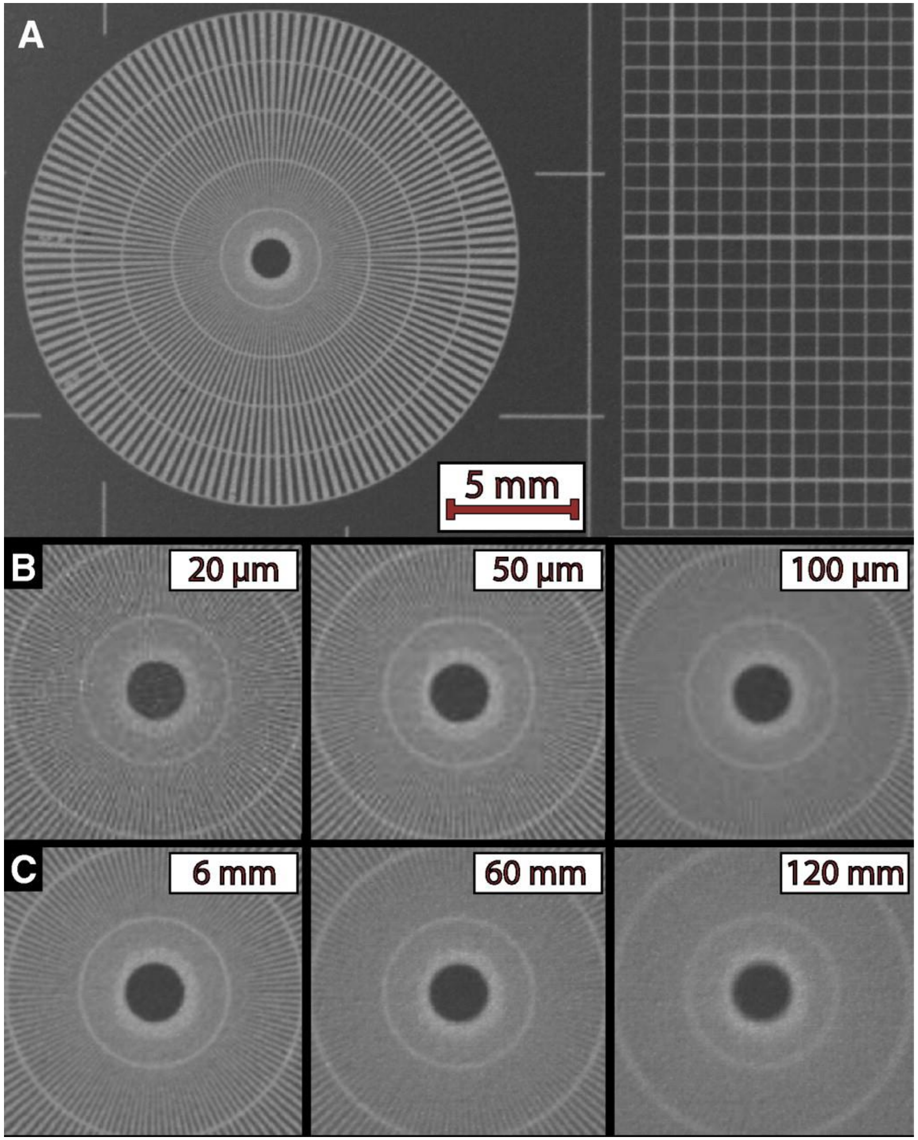
$^{155}Gd + {}^{1}n \Rightarrow {}^{156}Gd + \gamma{\acute{}}s + CE{\acute{}}s$ (7.9 MeV)

→

$^{157}Gd + {}^{1}n \Rightarrow {}^{158}Gd + \gamma{\acute{}}s + CE{\acute{}}s$ (8.5 MeV)

^{235}U, ^{239}Pu $^{1}n \Rightarrow$ fission products + 80 MeV

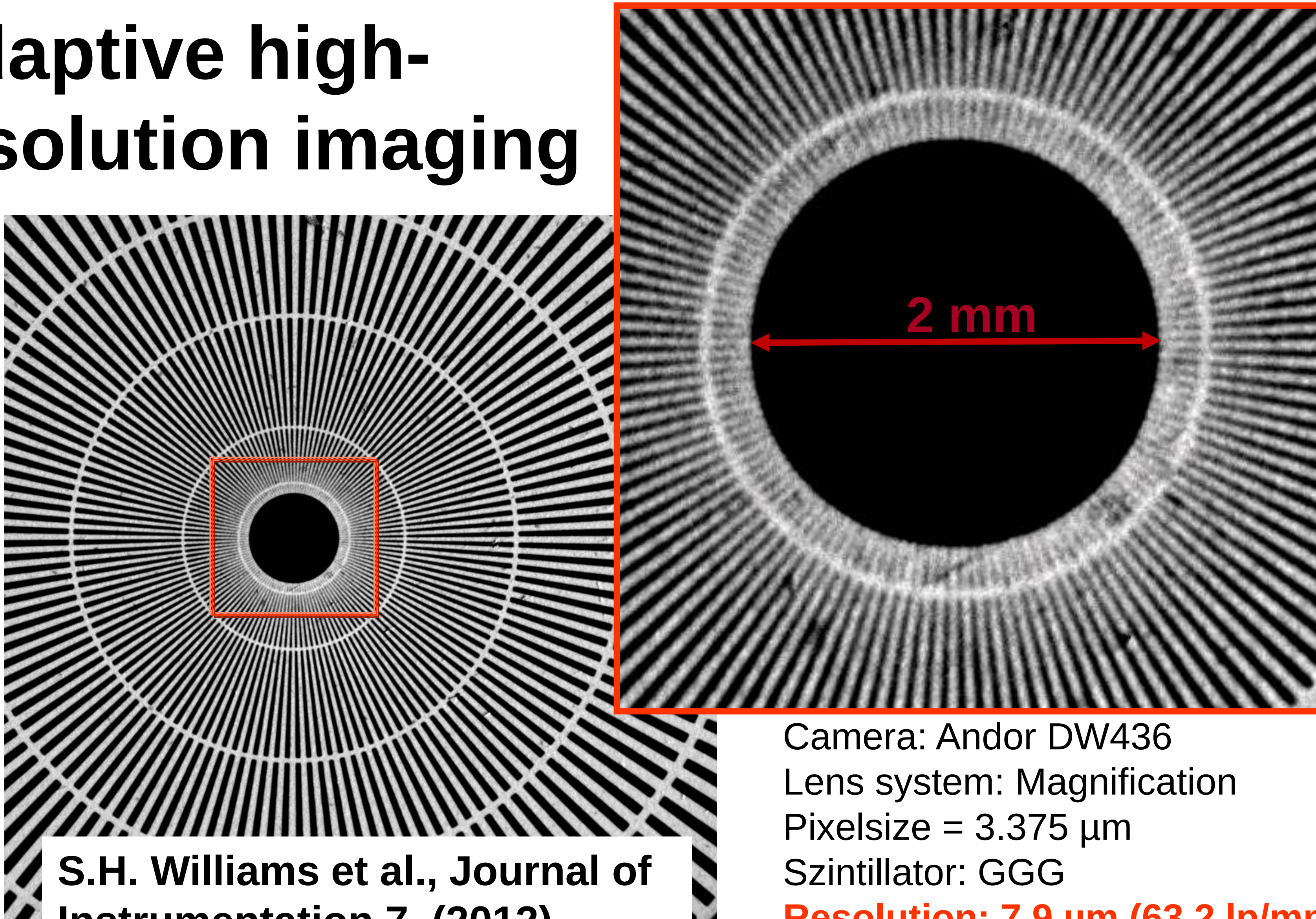
Scintillators, effect of thickness



(A) A radiograph of the Siemens star test pattern used to study the effect of scintillator thickness, exposure time, and impact of geometrical blurring.
(B) Images showing the center of the Siemens star for scintillators of different thicknesses.
(C) The same region imaged by a scintillator of 50 µm thickness. In each image the test pattern is placed further away from the scintillator, resulting in increased geometrical blurring.

K.-U. Hess et al., Advances in high-resolution neutron computed tomography: Adapted to the earth sciences , Geosphere (2011) 7 (6): 1294-1302.

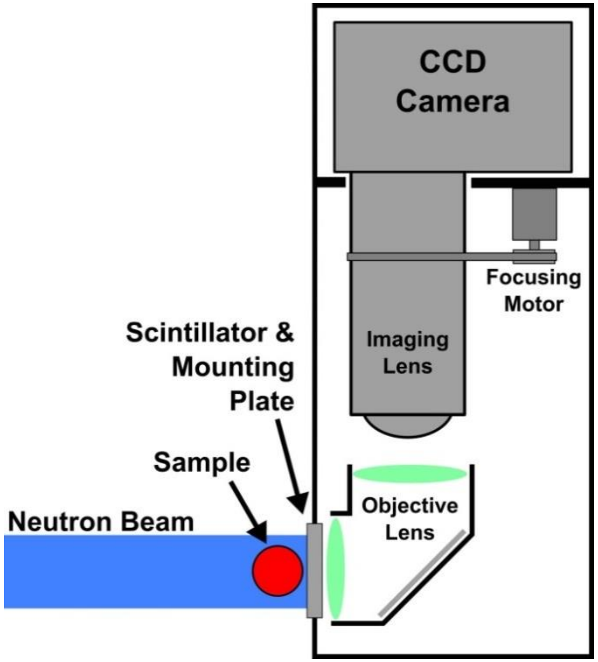
Adaptive high-resolution imaging

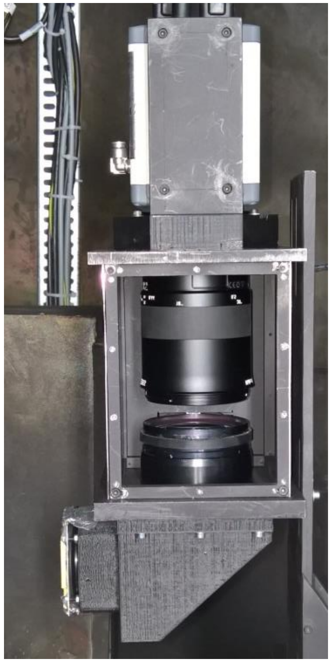


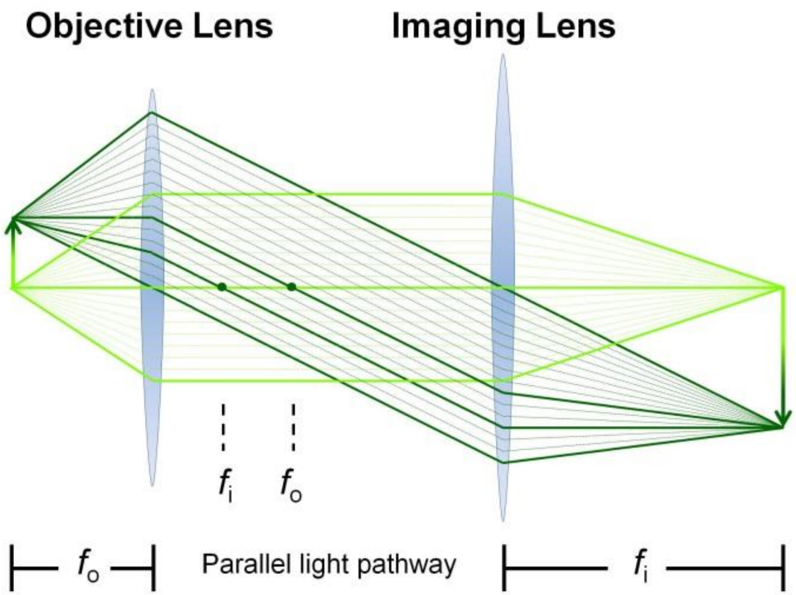
S.H. Williams et al., Journal of Instrumentation 7, (2012)

Camera: Andor DW436
Lens system: Magnification
Pixelsize = 3.375 µm
Szintillator: GGG
Resolution: 7.9 µm (63.2 lp/mm)

High resolution



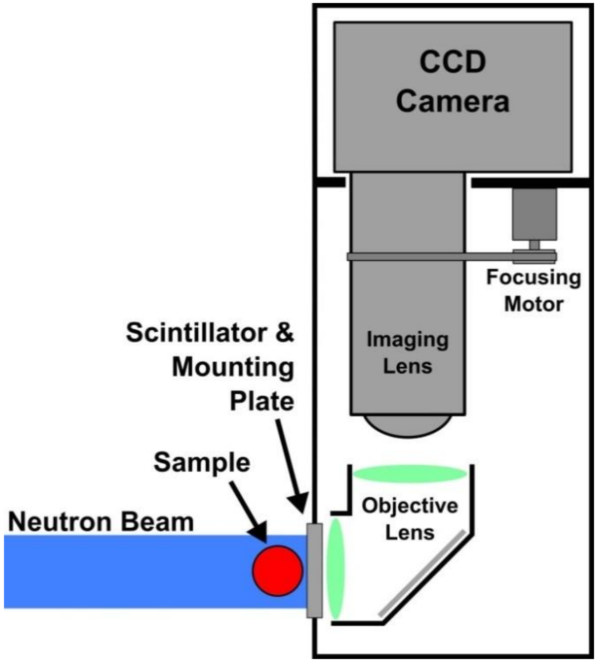


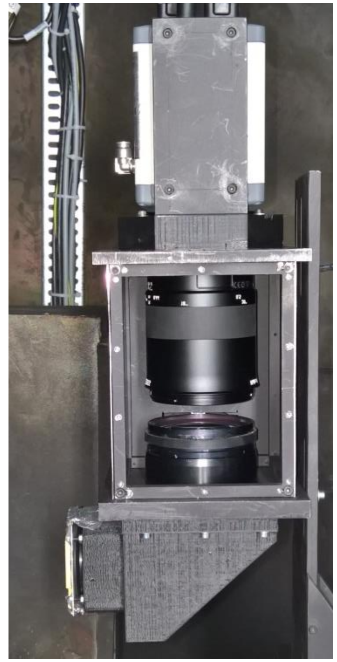


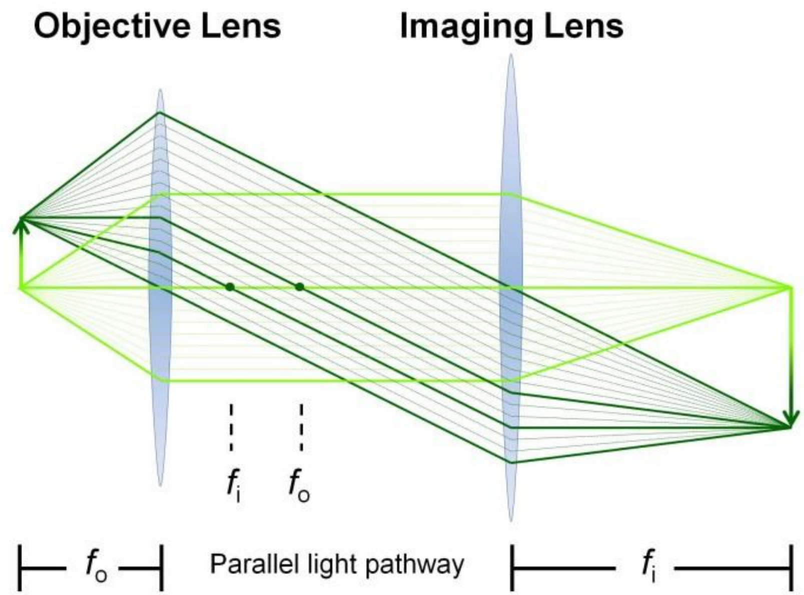
Obj. Lens/Img. Lens	*M*	P_{eff} *(μm)*	*FOV (mm)*
105 mm / 50 mm	2.10	6.429	13.2 × 13.2
200 mm / 100 mm	2.00	6.750	13.8 × 13.8
200 mm / 50 mm	4.00	3.375	6.9 × 6.9

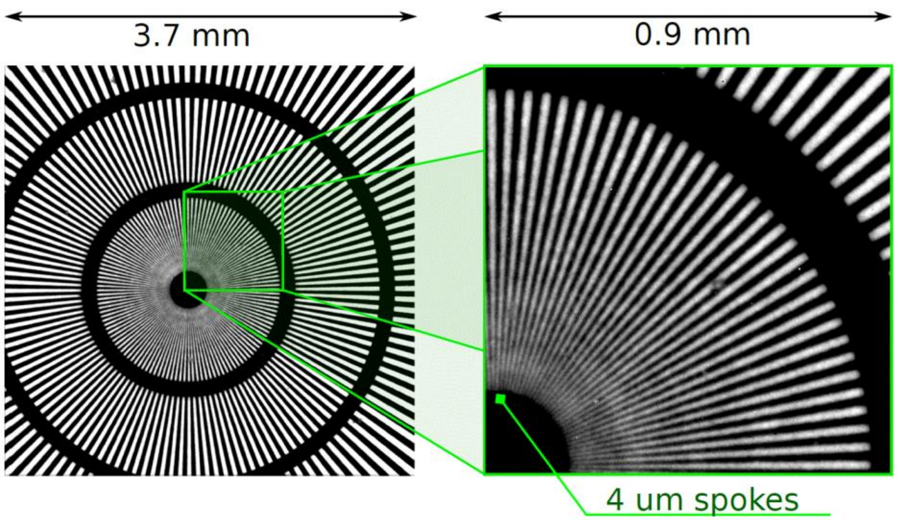
S. H. Williams et al, J. of Instrumentation (2012)

High resolution









spatial resolution
better than 5 µm

Tengattini, Alessandro, et al.
Optics Express 30.9 (2022)

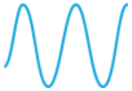
Resolution

- Beam optimisation
- Detector development

Contrast

- Neutron interaction with matter

- absorption

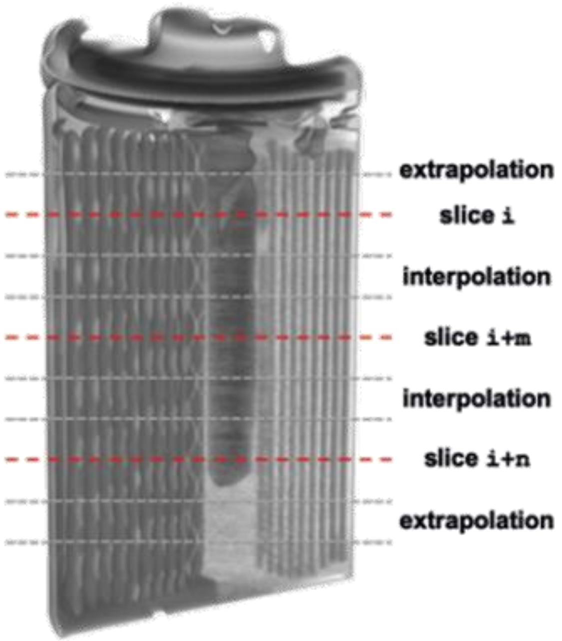


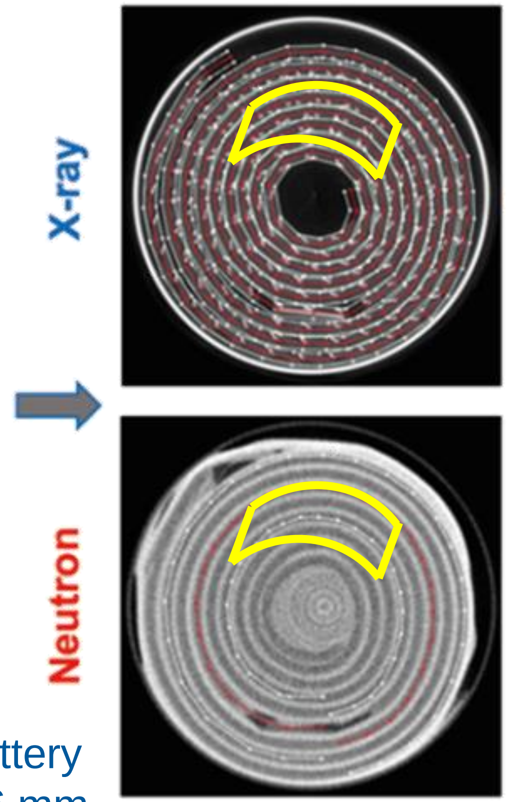
- scattering

- magnetic interaction

Ralf Ziesche
Paul Shearing

How to characterize lithium intercalation in batteries?





3D reconstruction of CR2 battery (Li_xMnO_2) with diameter of 26 mm.
(neutron tomography: pixel size: 13 µm, 600 projections /360°, time: 8 h)

- 3D+T investigation of batteries by dual-mode (X-ray/Neutron) tomography

Virtual unrolling of the electrodes for different discharge times.

Lithium intercalation can be analyzed dynamically.

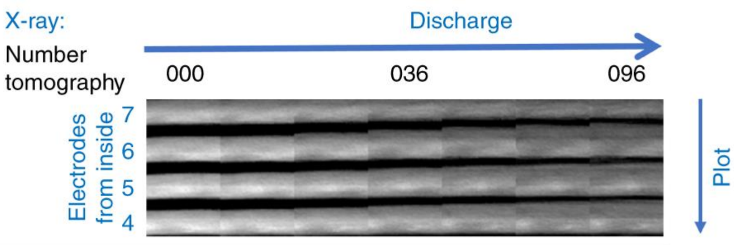
R. Ziesche *et al.*,
Nature communications 11.1 (2020): 1-11.

➔ **Analysis of the dual-mode tomography data**

➡ **Temporally and spatially resolved tracking of lithium intercalation.**

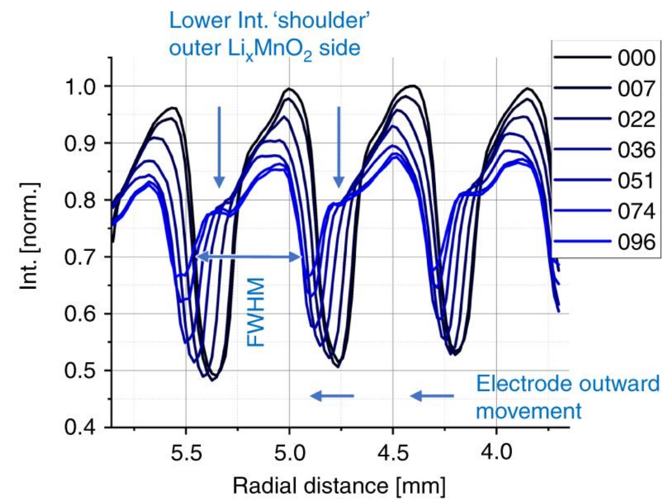
Ralf Ziesche
Paul Shearing

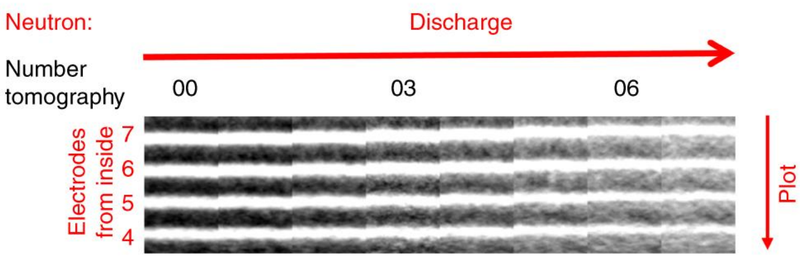
How to characterize lithium intercalation in batteries?



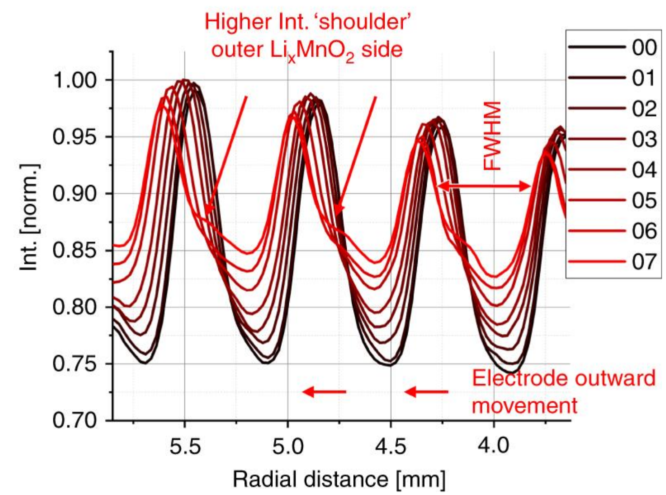
Capacity [|mAh|]	0	48	144	241	336	474	605
Breadth [µm]	389	414	431	442	467	486	495

1 mm





Capacity [|mAh|]	0	45	135	226	316	449	581	745
Breadth [µm]	386	392	423	427	453	461	488	501

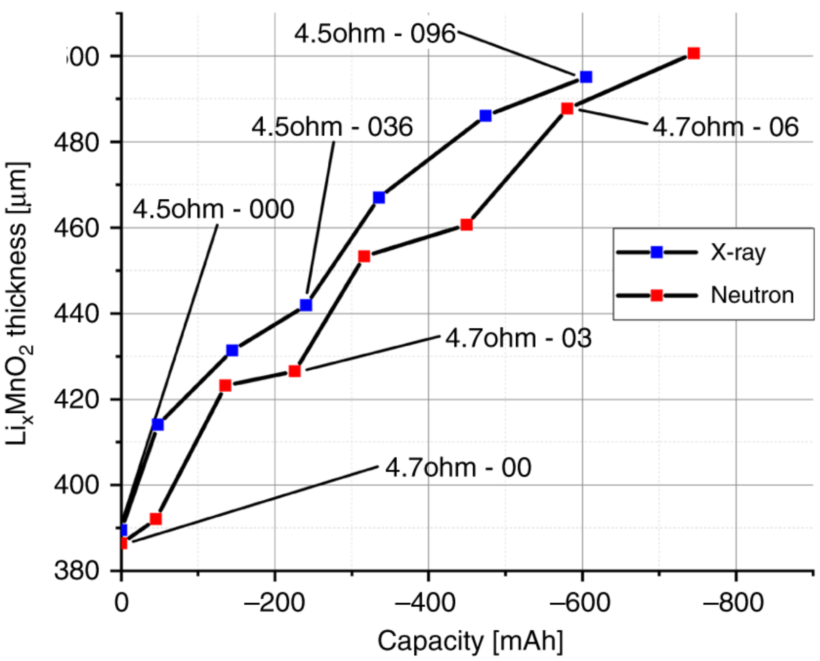


R. Ziesche *et al*., Nature communications 11.1 (2020): 1-11.

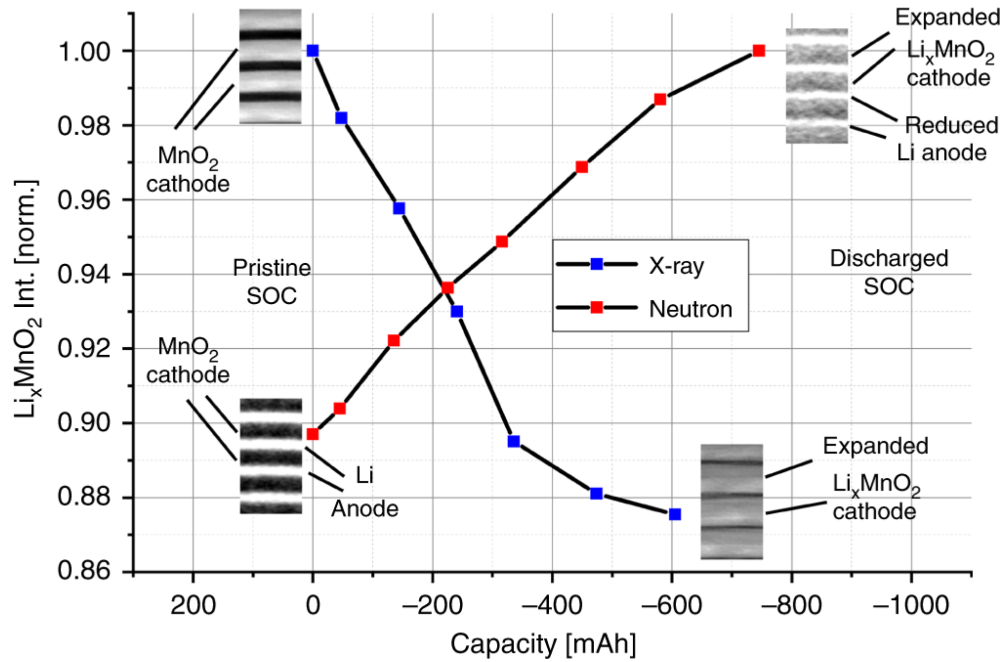
Ralf Ziesche
Paul Shearing

How to characterize lithium intercalation in batteries?

Electrode thickness dependence



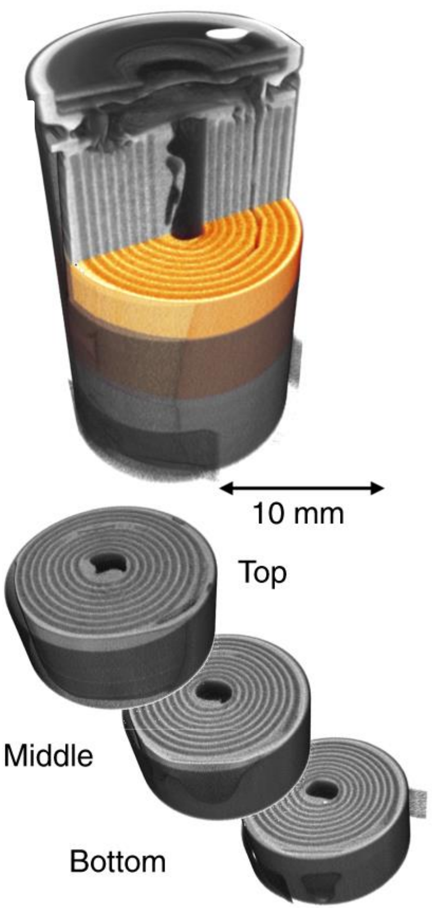
Lithium consumption

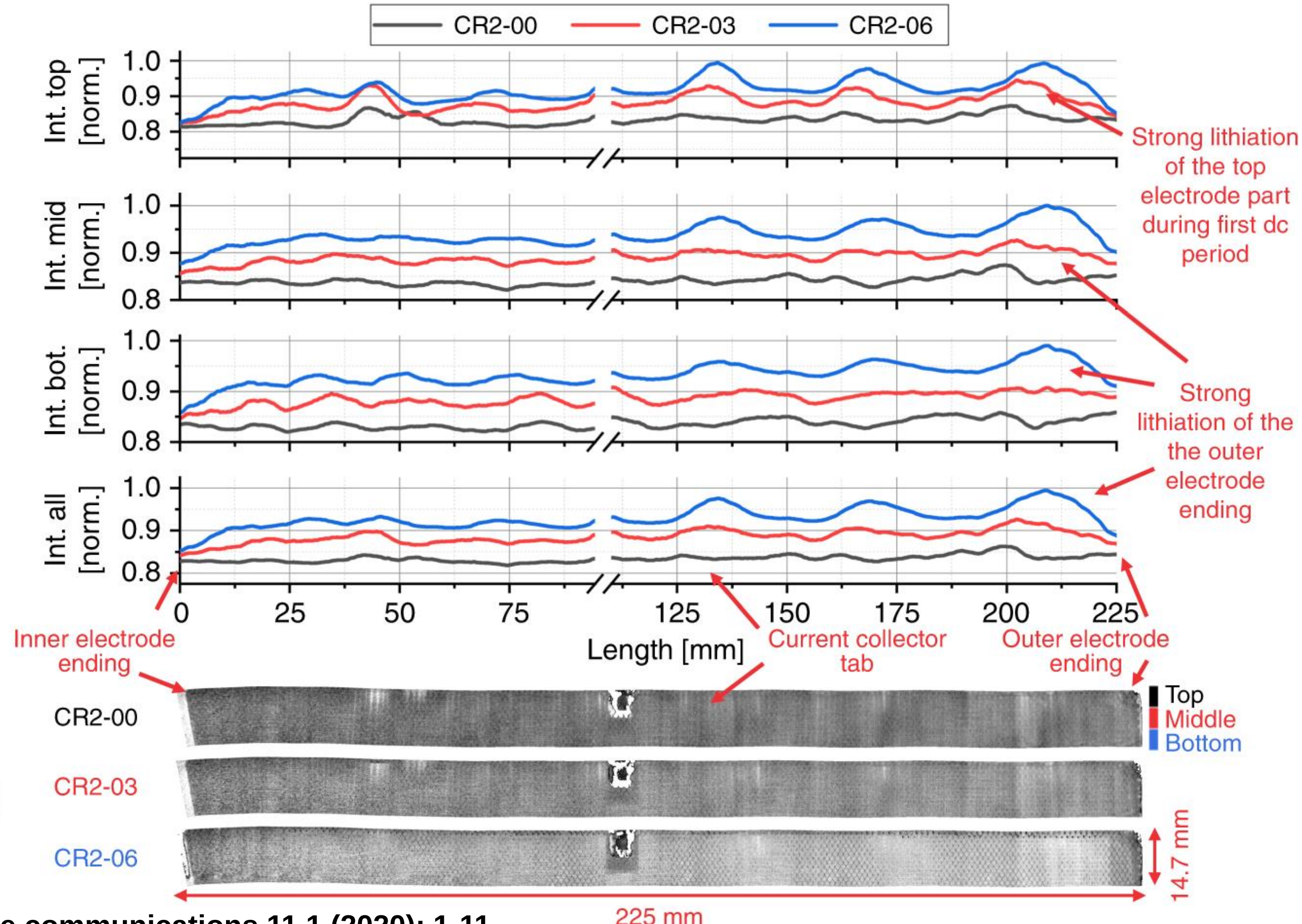


R. Ziesche *et al*., Nature communications 11.1 (2020): 1-11.

Ralf Ziesche
Paul Schering

How to characterize lithium intercalation in batteries?





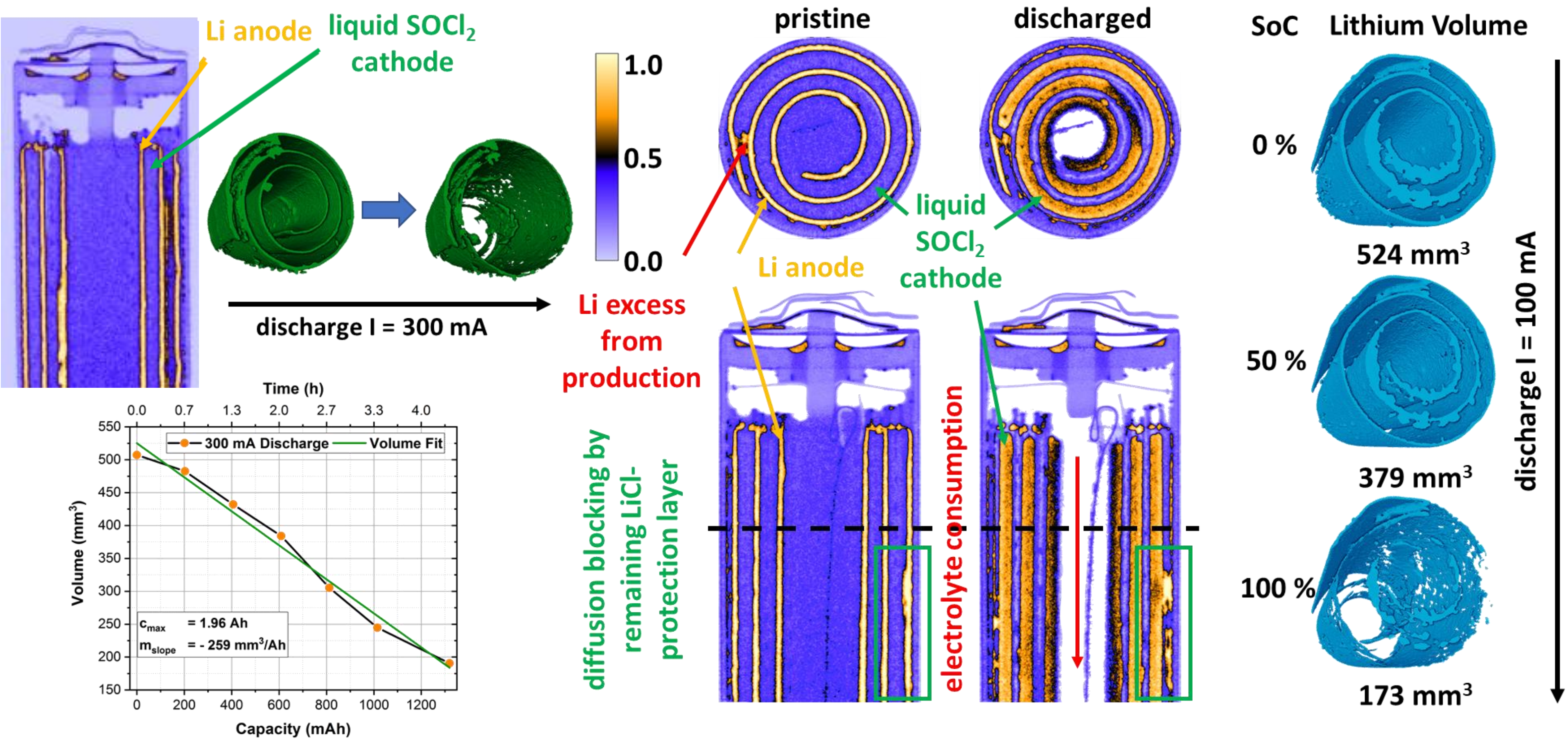
R. Ziesche *et al.*, Nature communications 11.1 (2020): 1-11.

A. Tengattini
L. Helfen
N. Lenoir

Ralf Ziesche
Paul Schering

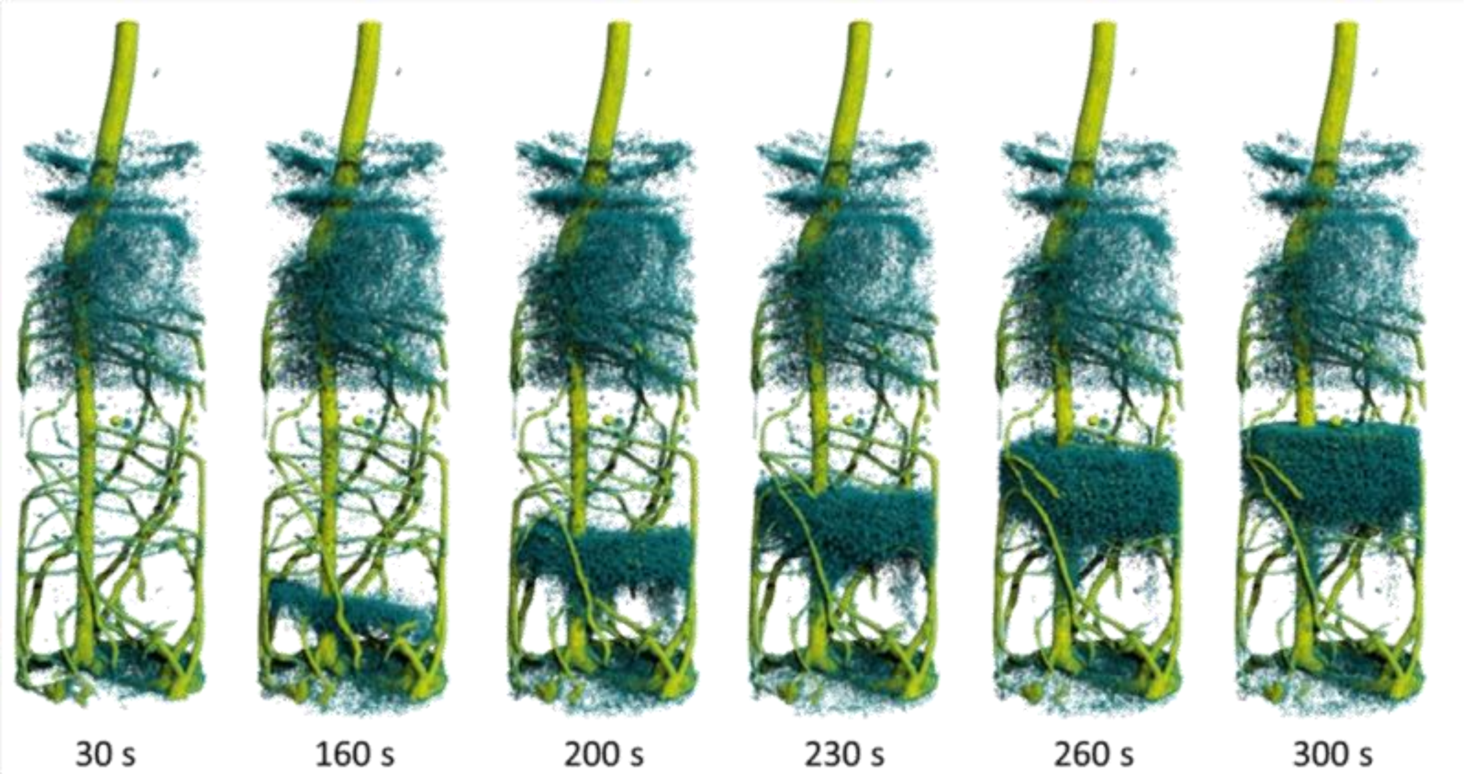
How to characterize lithium diffusion in batteries?

4D Study of $SOCl_2$ Battery (pixel size: 8 µm, time step: 7.5 min)



R. Ziesche *et al*., Journal of Electrochemical Society 167 (2020)

High-speed tomography

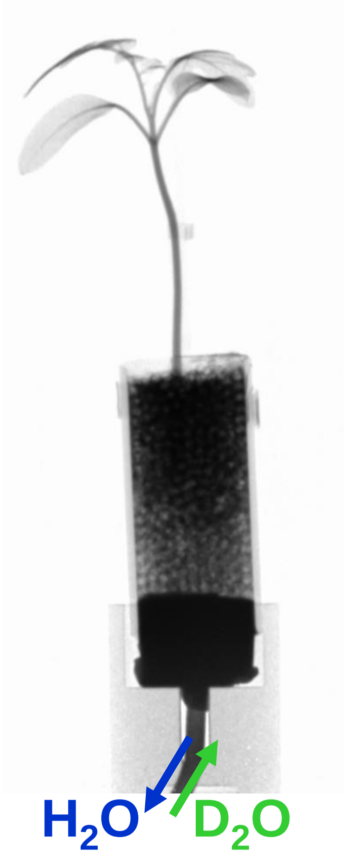


C. Tötzke *et al.* Scientific Reports 7, 61924, (2017)

Plant's physiology

University of Potsdam
Christian Tötzke
Sascha E. Oswald

How to observe the water uptake in plant's root



- *In-operando 3D* visualization of water distribution

Water uptake dynamics revealed with D-H contrast

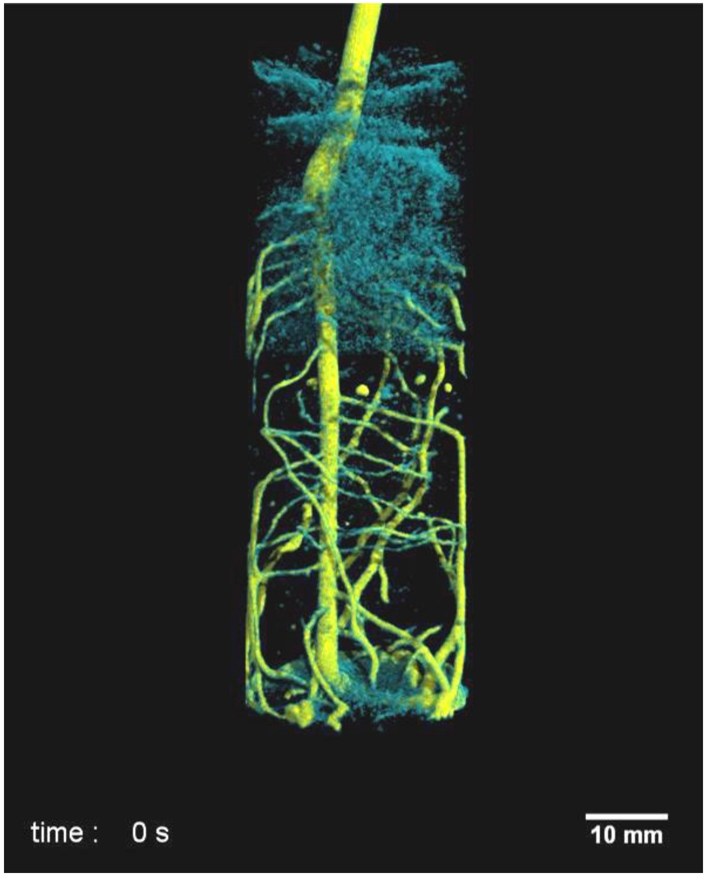
Insights in the water uptake mechanisms in the root system

→ Observation of the dynamic processes in root system

➡ Learning about the root-soil interaction mechanisms

University of Potsdam
Christian Tötzke
Sascha E. Oswald

How to observe the water uptake in plant's root



High-speed (on-the-fly) neutron tomography

resolution: 150 µm
exposure: 0.05 s
200 projections/180°

10 s / tomography

➔ Observation of the dynamic processes in root system

➔ Learning about the root-soil interaction mechanisms

Plant's physiology

University of Potsdam
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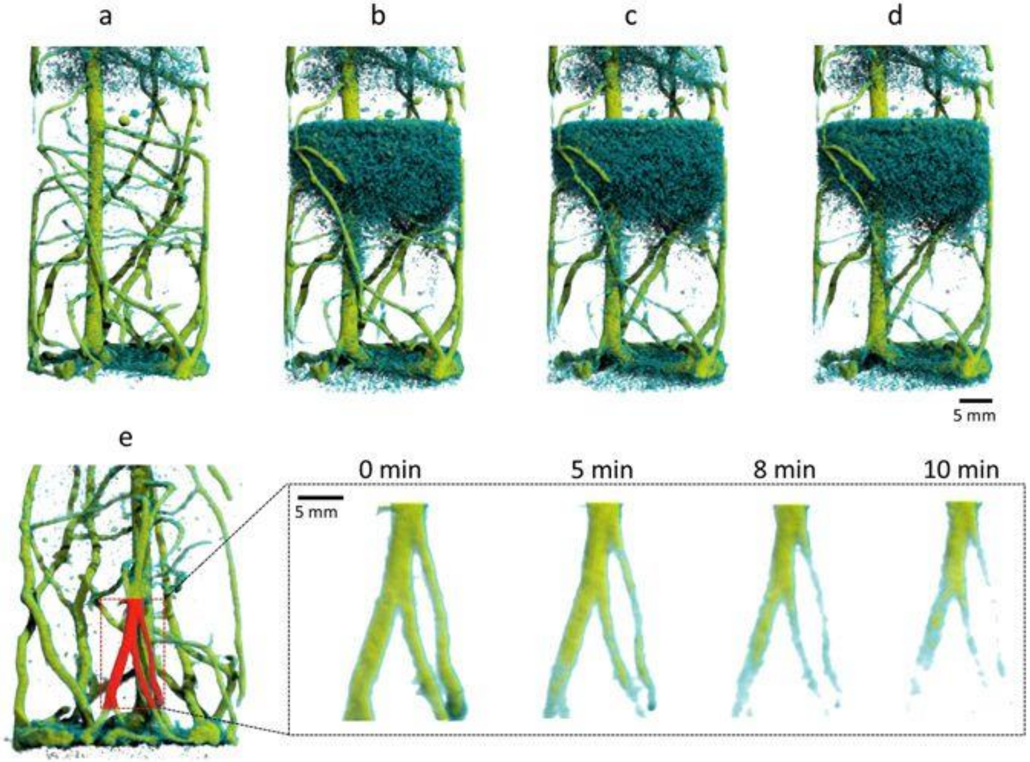
How to observe the water uptake in plant's root



Time series of neutron tomograms at (a) 0 min; (b) 5 min; (c) 8 min and (d) 10 min after feeding D_2O.

High-speed (on-the-fly) neutron tomography

resolution: 150 µm

exposure: 0.05 s

200 projections/180°

10 s / tomography

Ch. Tötzke, et al. *Scientific reports* 7.1 (2017): 6192.

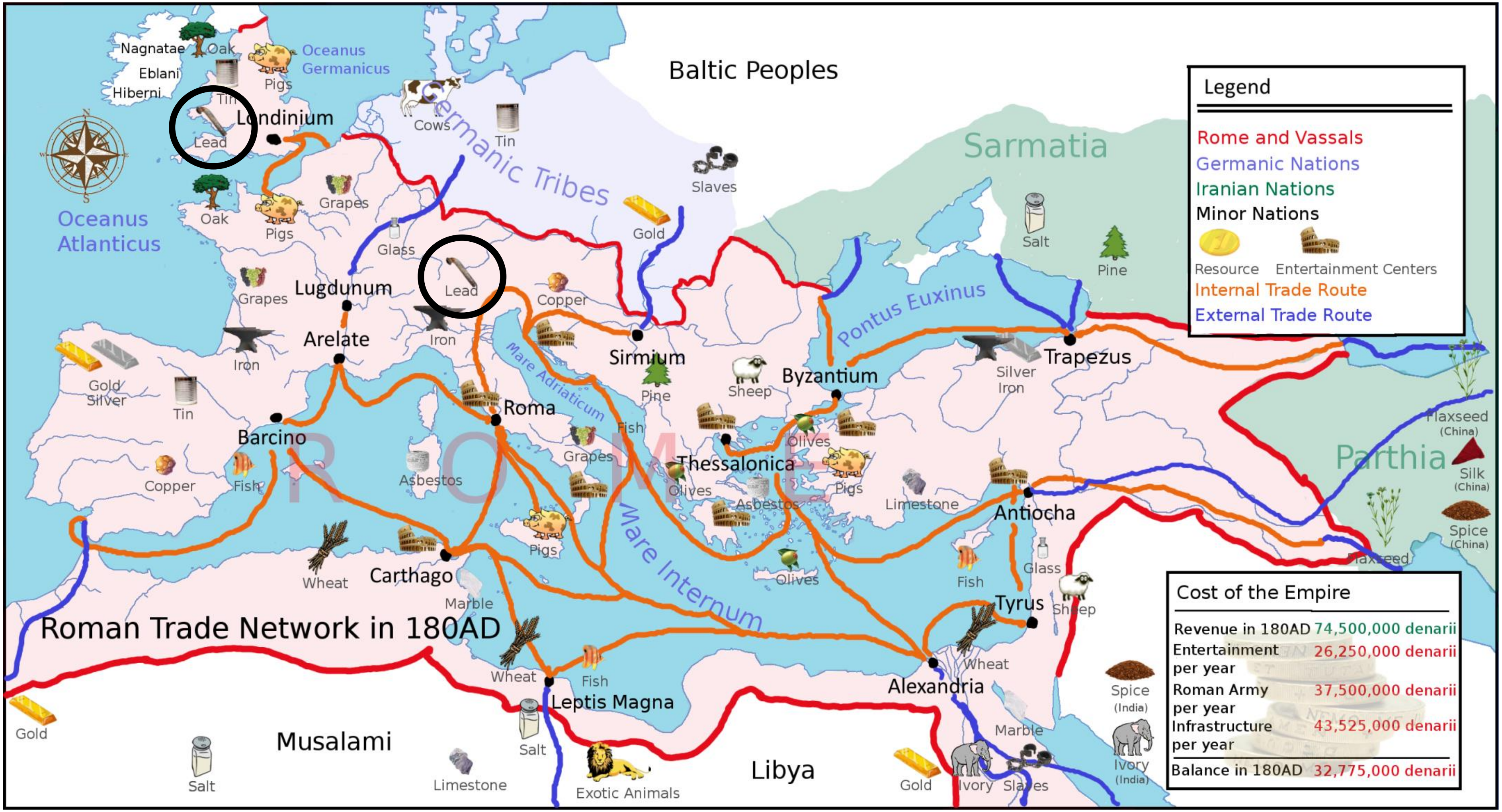
→ **Observation of the dynamic processes in root system**

➡ **Learning about the root-soil interaction mechanisms**

Attenuation Contrast

Shipwrecks

https://commons.wikimedia.org/wiki/File:Europe_180ad_roman_trade_map.png

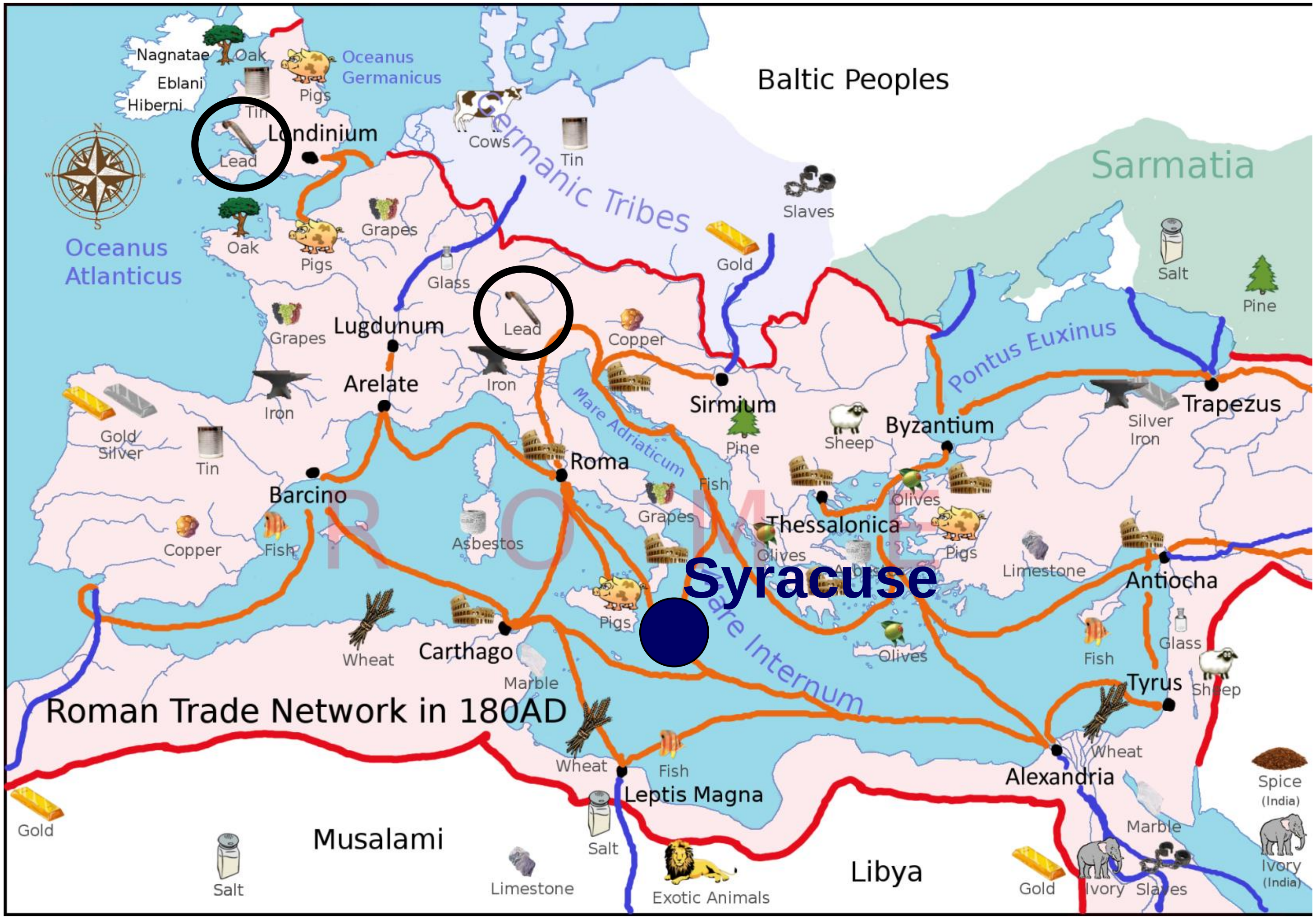


All routes lead to Rome: A map of Roman ports and trade routes

Attenuation Contrast

Shipwrecks

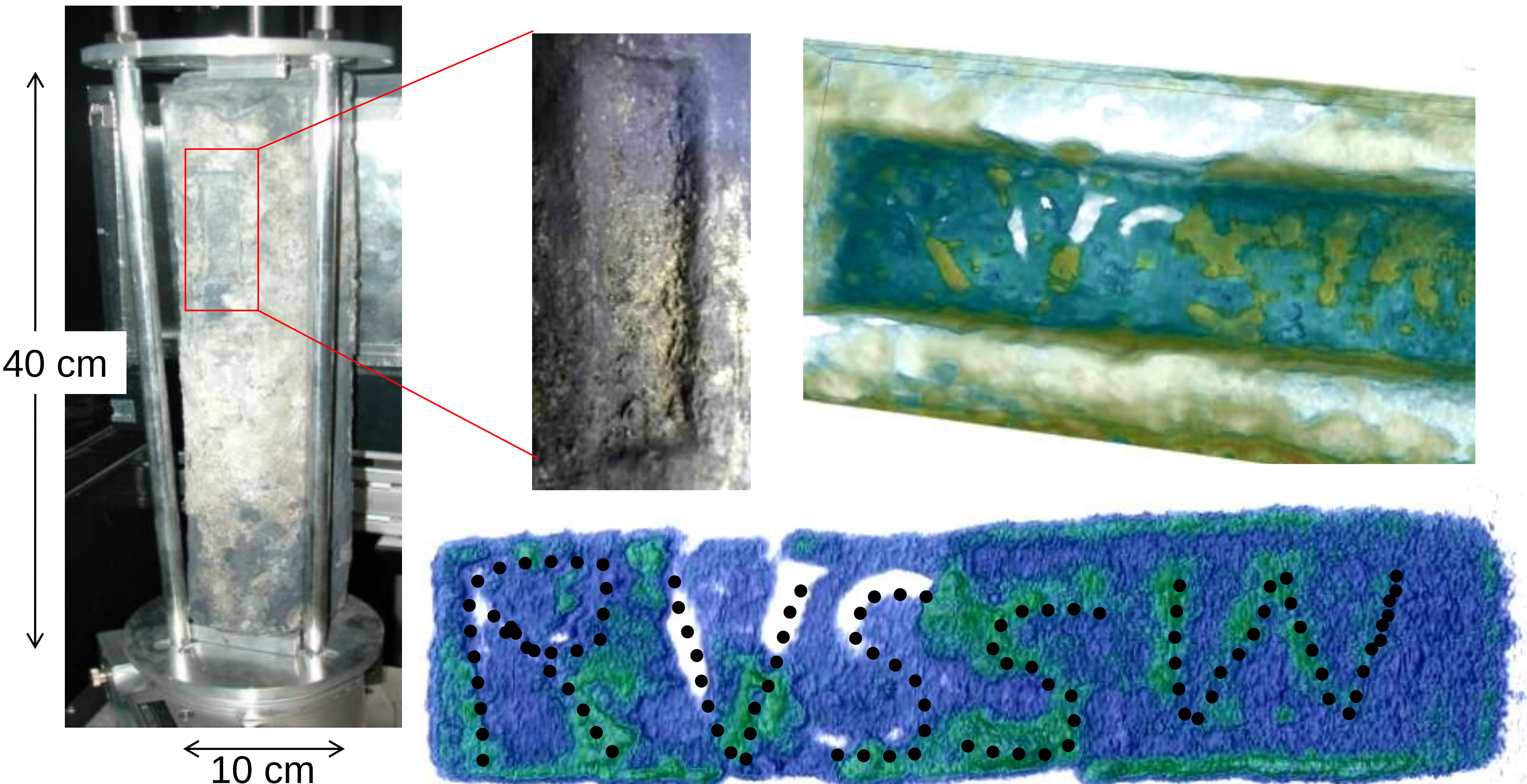
https://commons.wikimedia.org/wiki/File:Europe_180ad_roman_trade_map.png



All routes lead to Rome: A map of Roman ports and trade routes

Attenuation Contrast

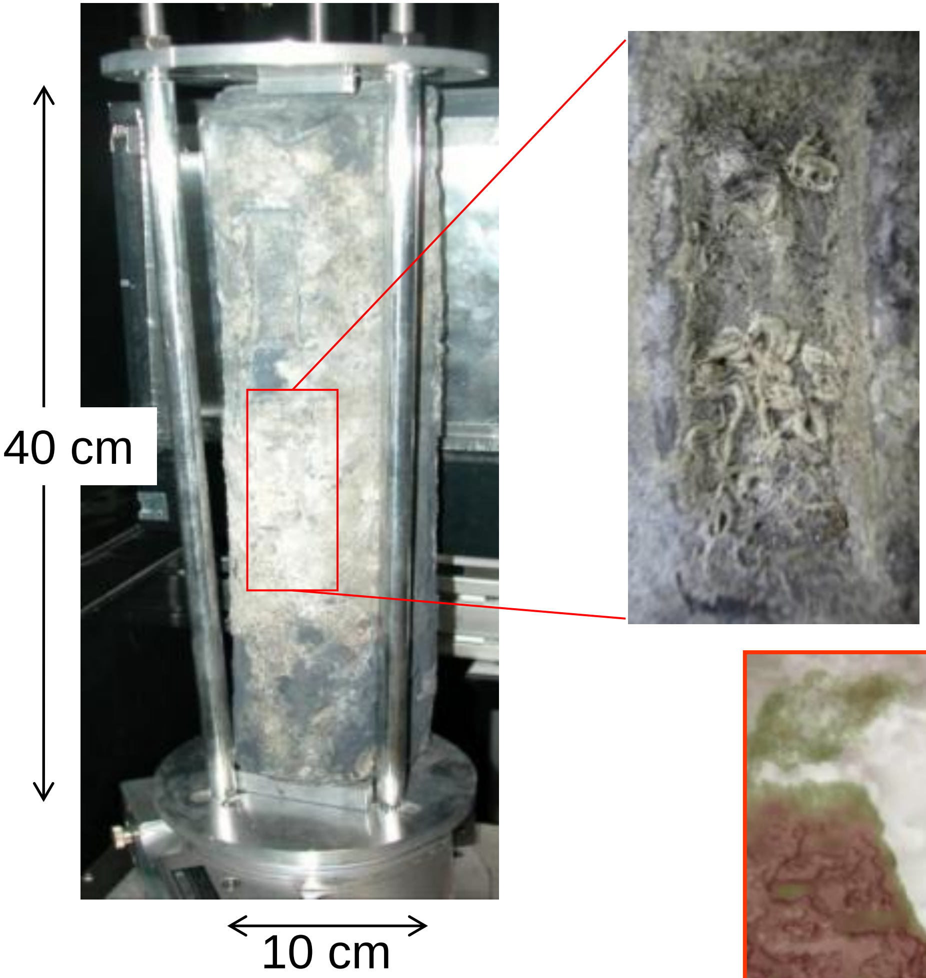
Lead blocks recovered near the UNESCO World Heritage Site Syracuse.
Presumably I century B.C. (Roman Imperial Age).

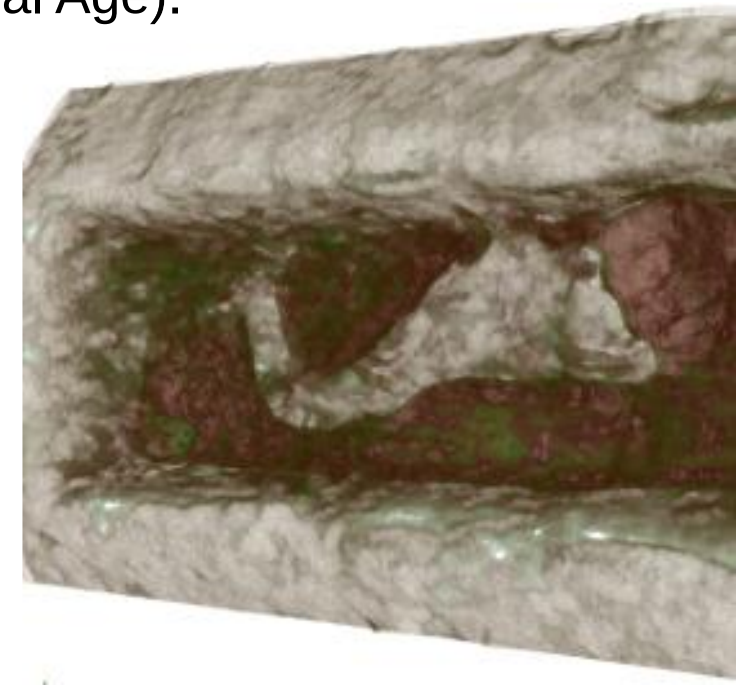


Triolo, R. et al, Neutron tomography of ancient lead artefacts, Anal. Methods 6 (2014) 2390-2394

Attenuation Contrast

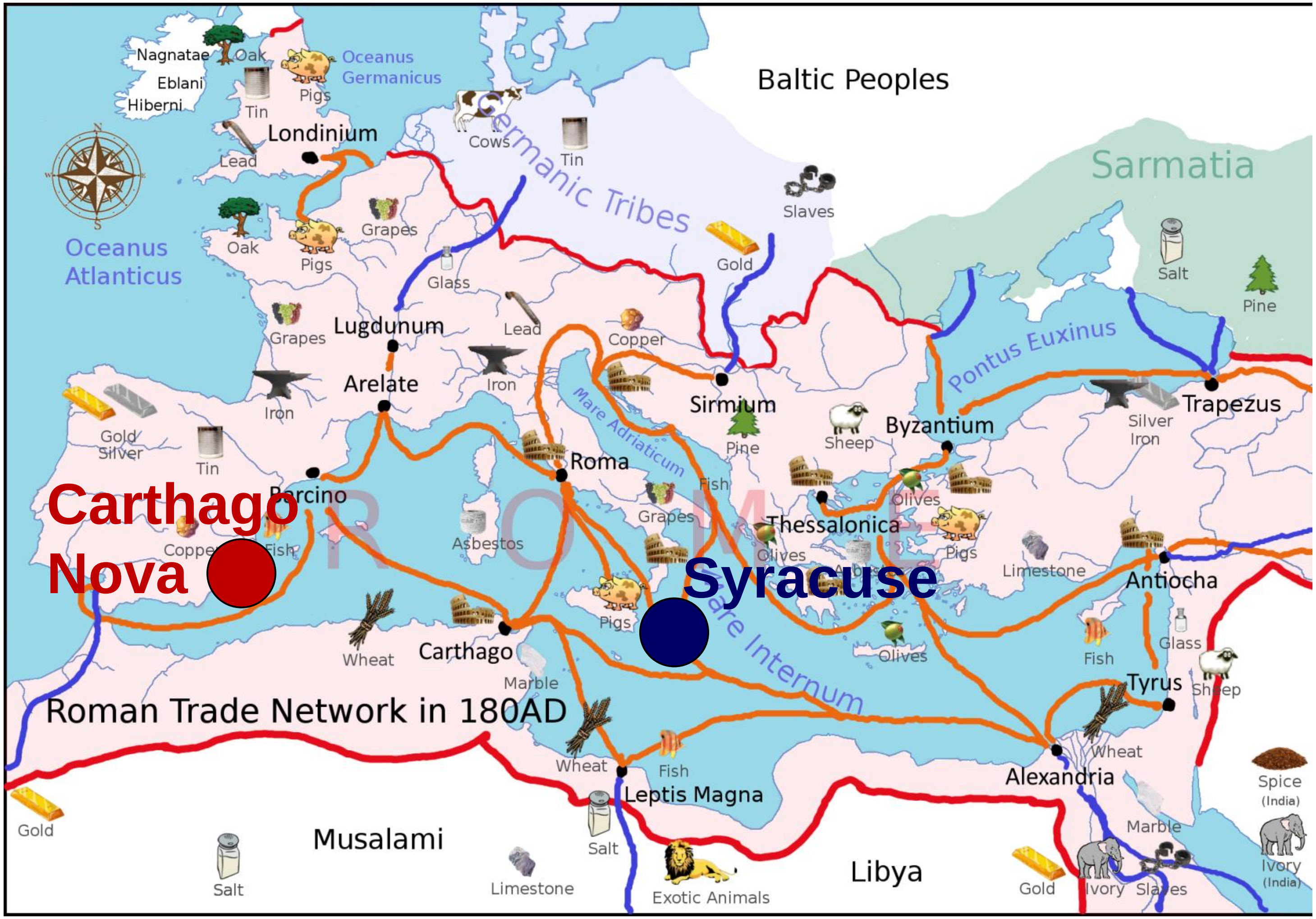
Lead blocks recovered near the UNESCO World Heritage Site Syracuse. Presumably I century B.C. (Roman Imperial Age).





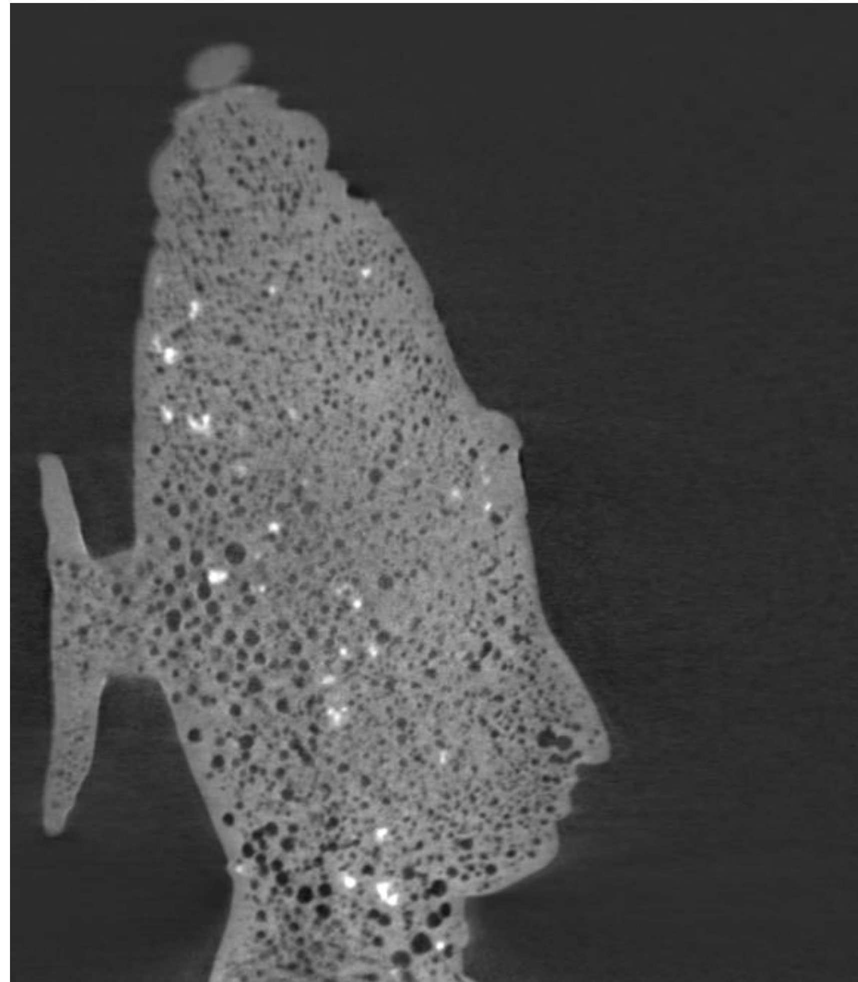
Attenuation Contrast

https://commons.wikimedia.org/wiki/File:Europe_180ad_roman_trade_map.png



Triolo, R., et al. *Analytical Methods* 6.7 (2014): 2390-2394.

Neutron tomography of bronze statues



RIJKS MUSEUM
amsterdam

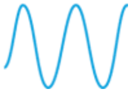
Resolution

- Beam optimisation
- Detector development

Contrast

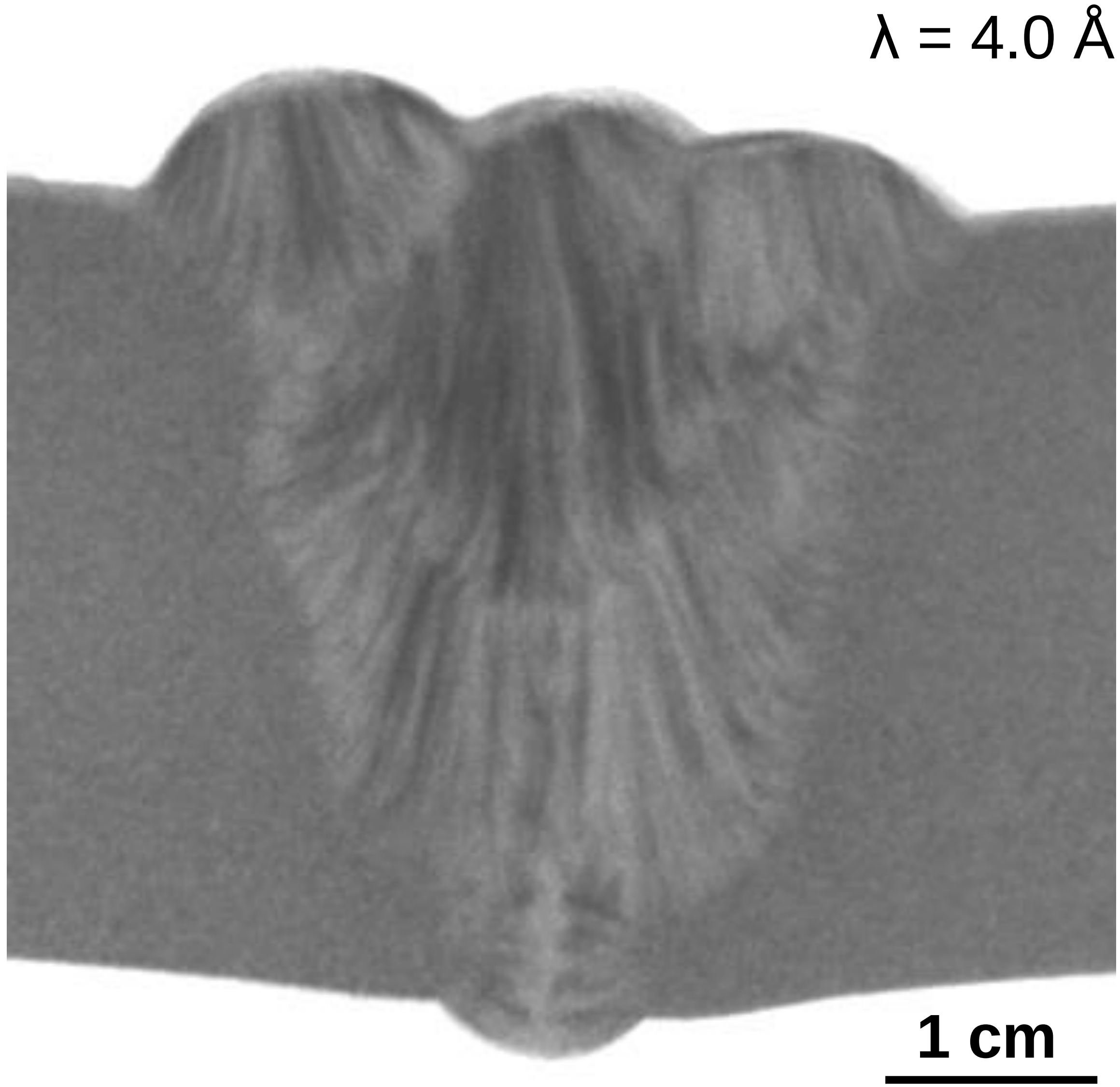
- Neutron interaction with matter

- absorption


- scattering

- magnetic interaction

Diffraction Contrast



Diffraction Contrast

Beam monochromatisation

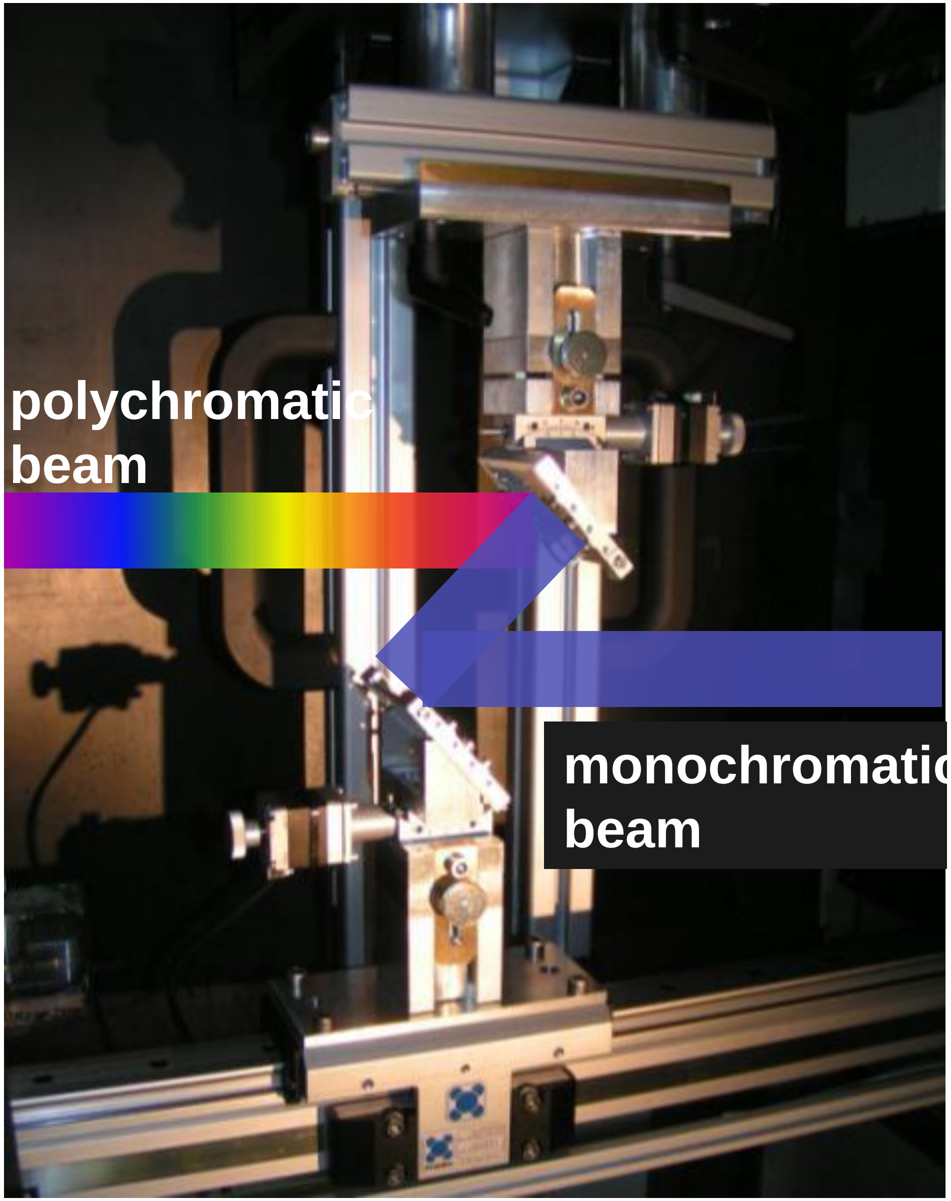
Double crystal monochromator: PCG crystals (mosaicity of 0.8°)

Range: 2.0 – 6.5 Å

Resolution ($\Delta\lambda/\lambda$): ~ 3%

Neutron flux: ~ 4×10^5 n/cm^{2}s (at λ=3.0 Å)

Beam size: 5 x 20 cm^2



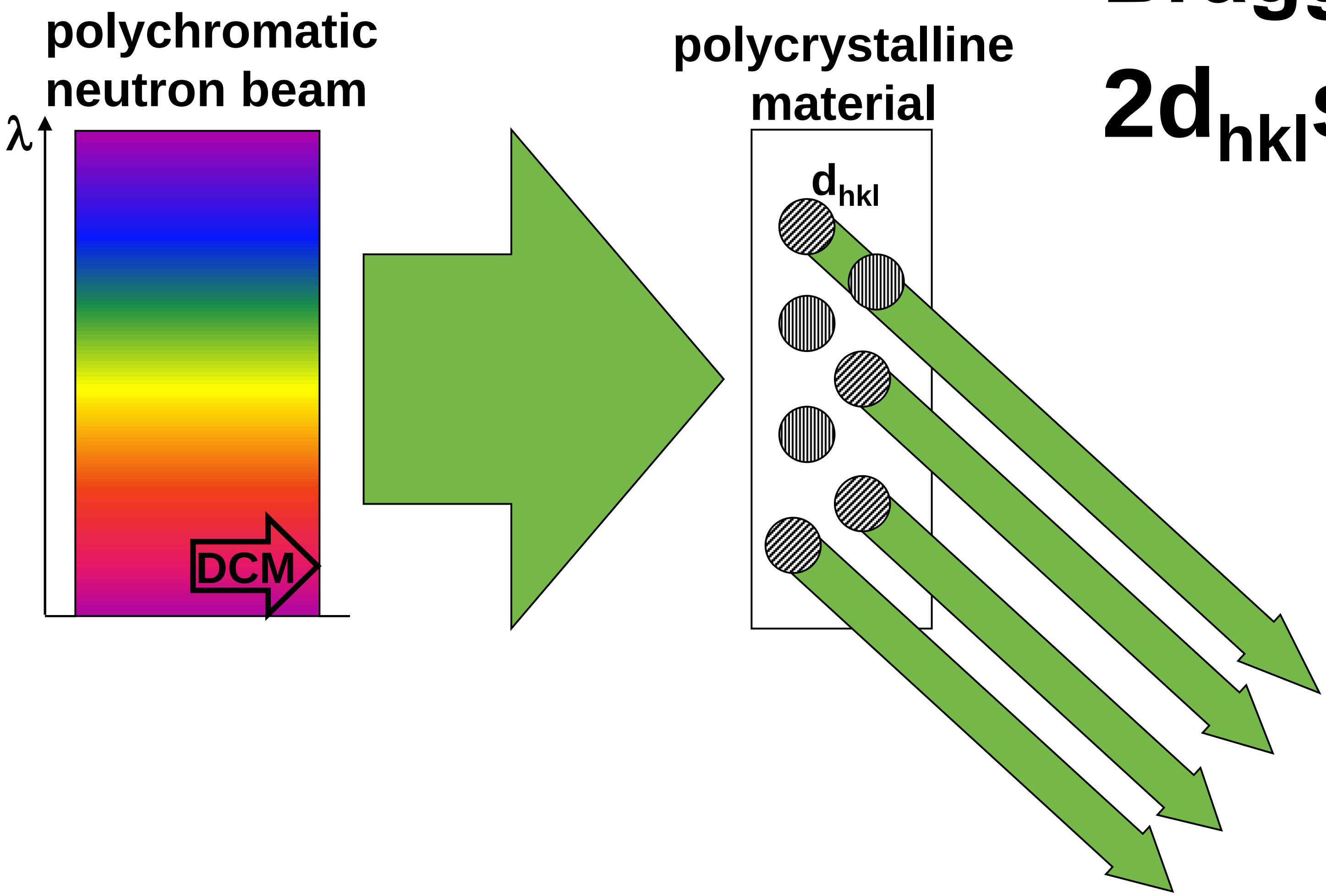
N. Kardjilov, et al. NIMA 605.1 (2009), 13-15.

Diffraction Contrast

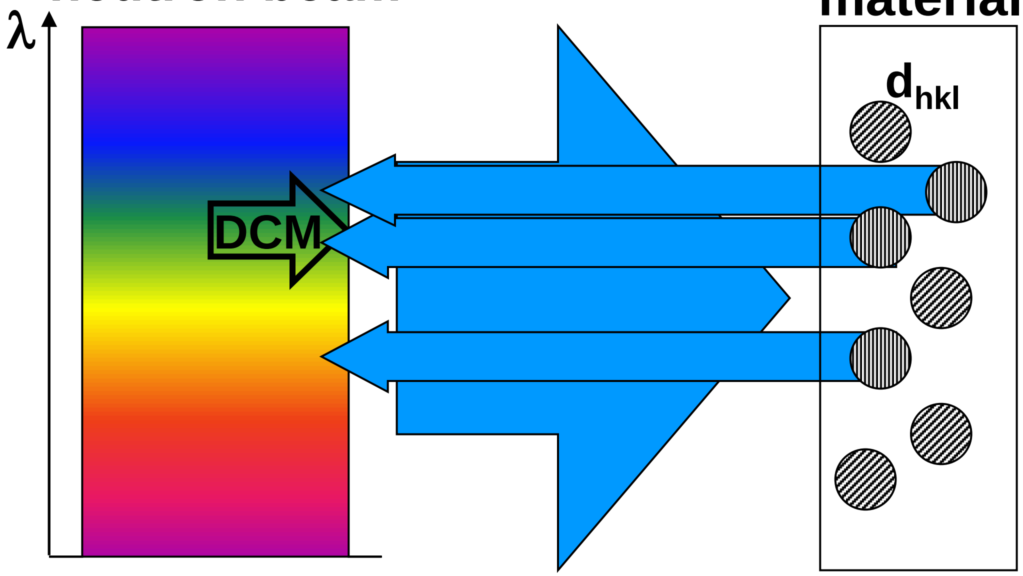
Coherent scattering – Bragg edges

Bragg's law

$$2d_{hkl}\sin\theta=\lambda$$



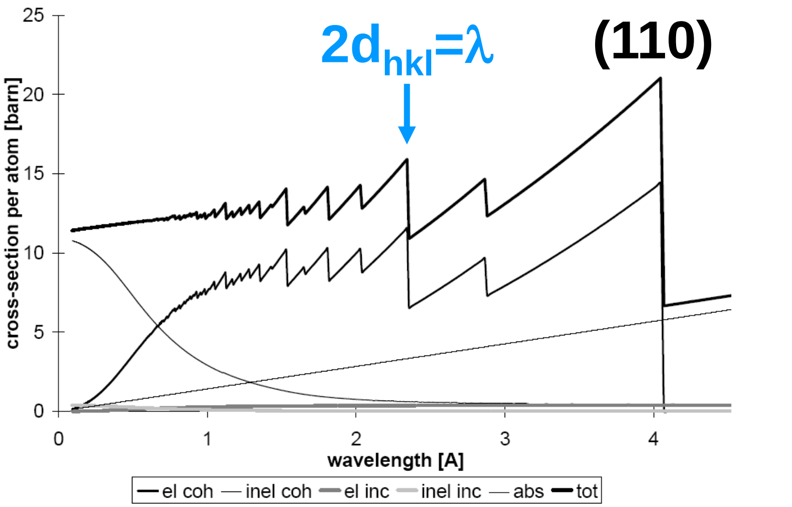
Coherent scattering – Bragg edges



Bragg's law

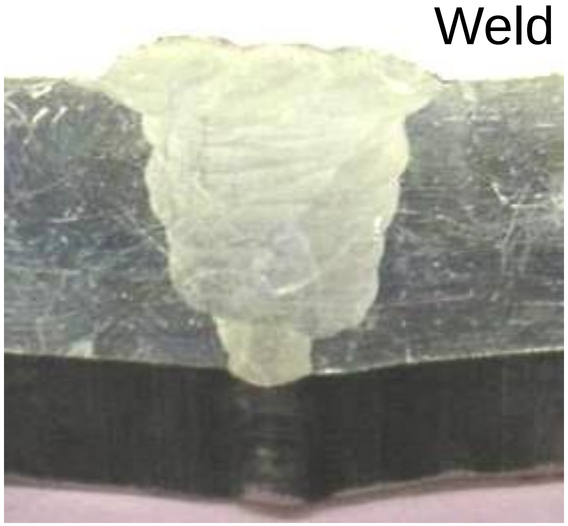
$$2d_{hkl}\sin 90° = \lambda$$

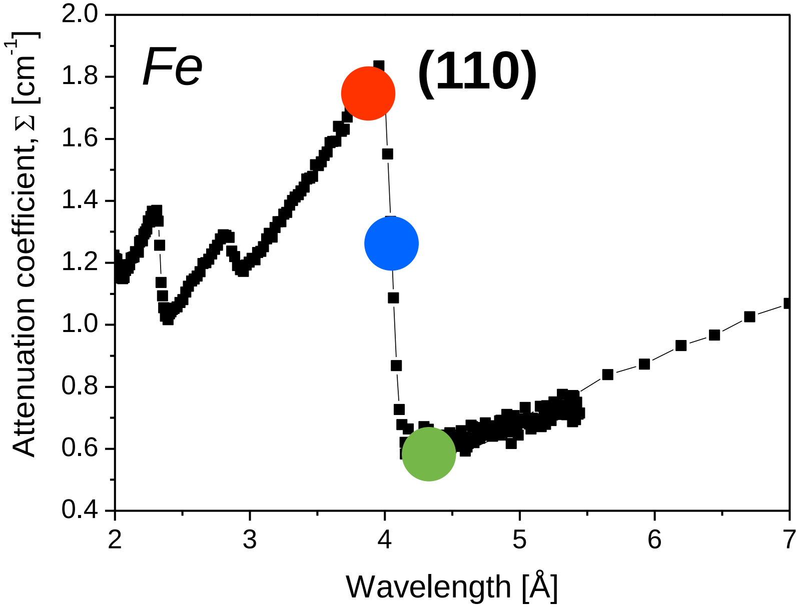
Cross-sections of iron per ator

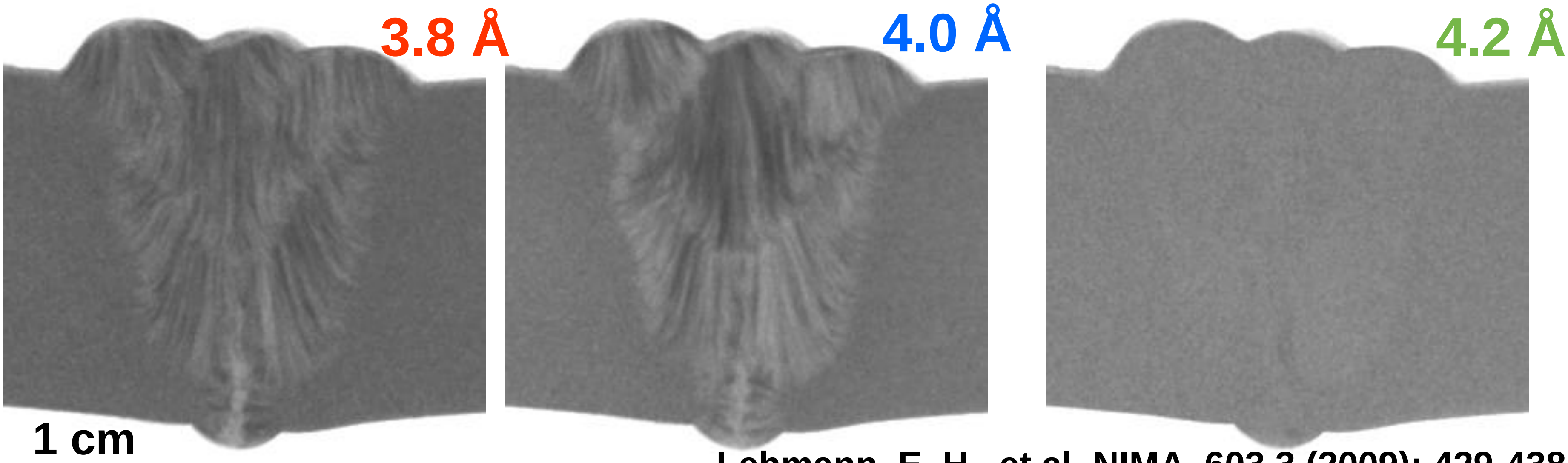


Neutron imaging

Energy-selective radiography

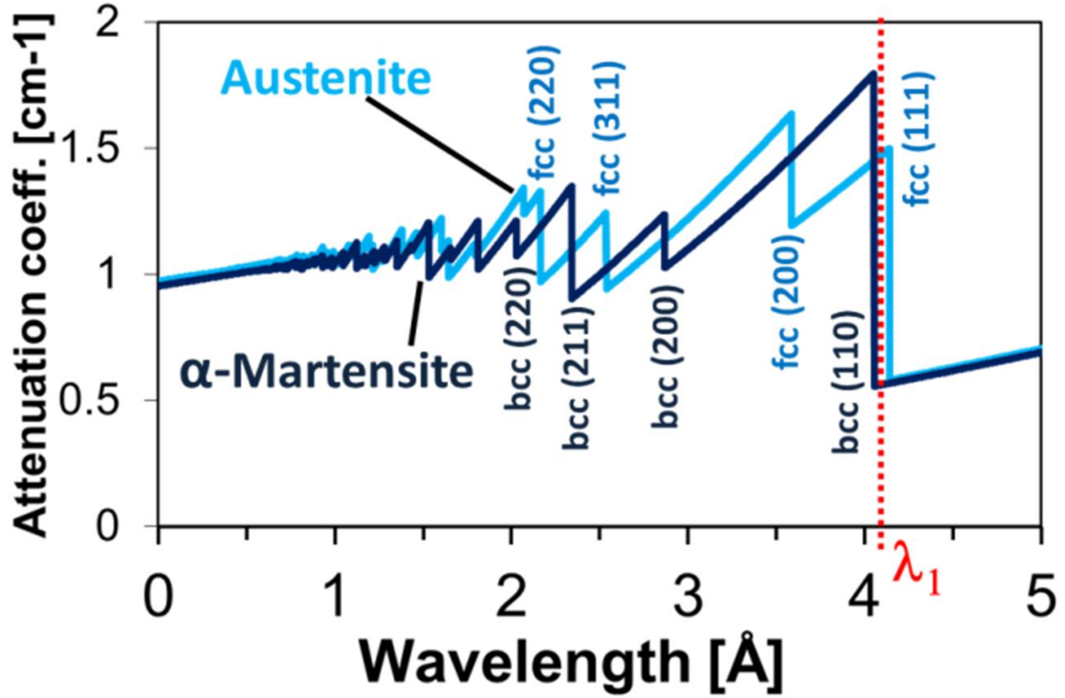


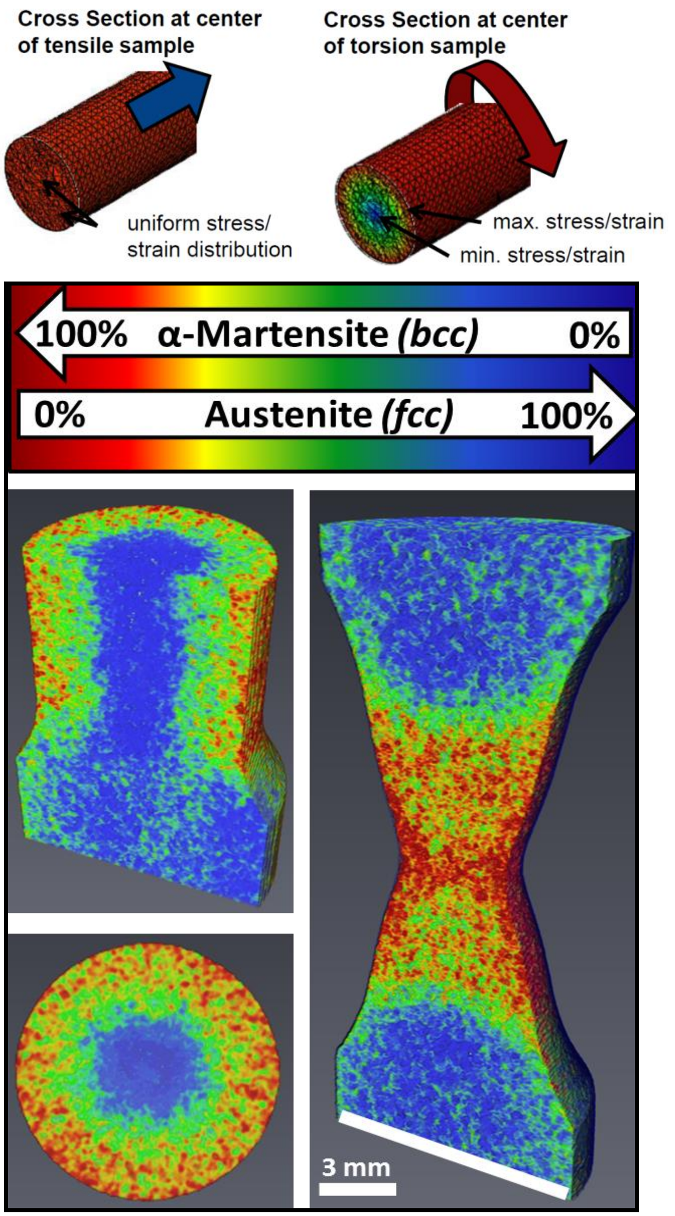




Lehmann, E. H., et al. NIMA 603.3 (2009): 429-438.

3D Phase mapping in metals

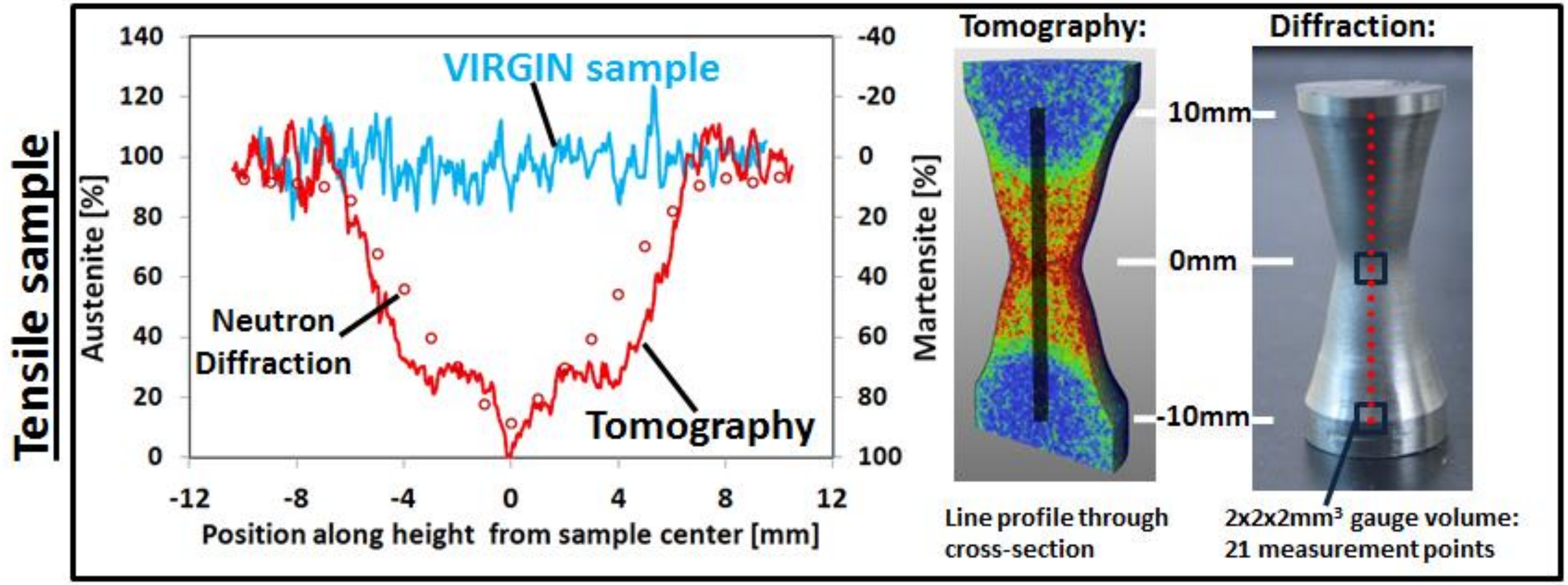


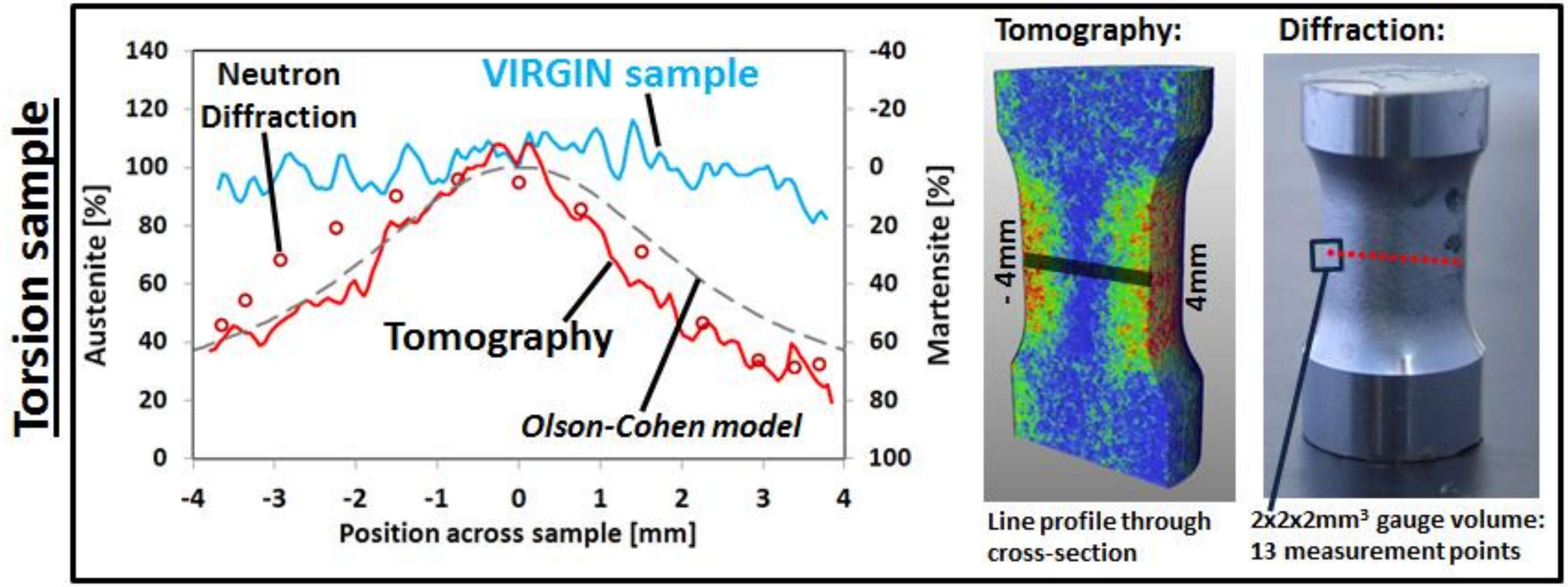


Energy-selective neutron tomography of TRIP-steel

R. Woracek et al., **Advanced Materials 26** (2014)

Diffraction Contrast





Resolution

- Beam optimisation
- Detector development

Contrast

- Neutron interaction with matter

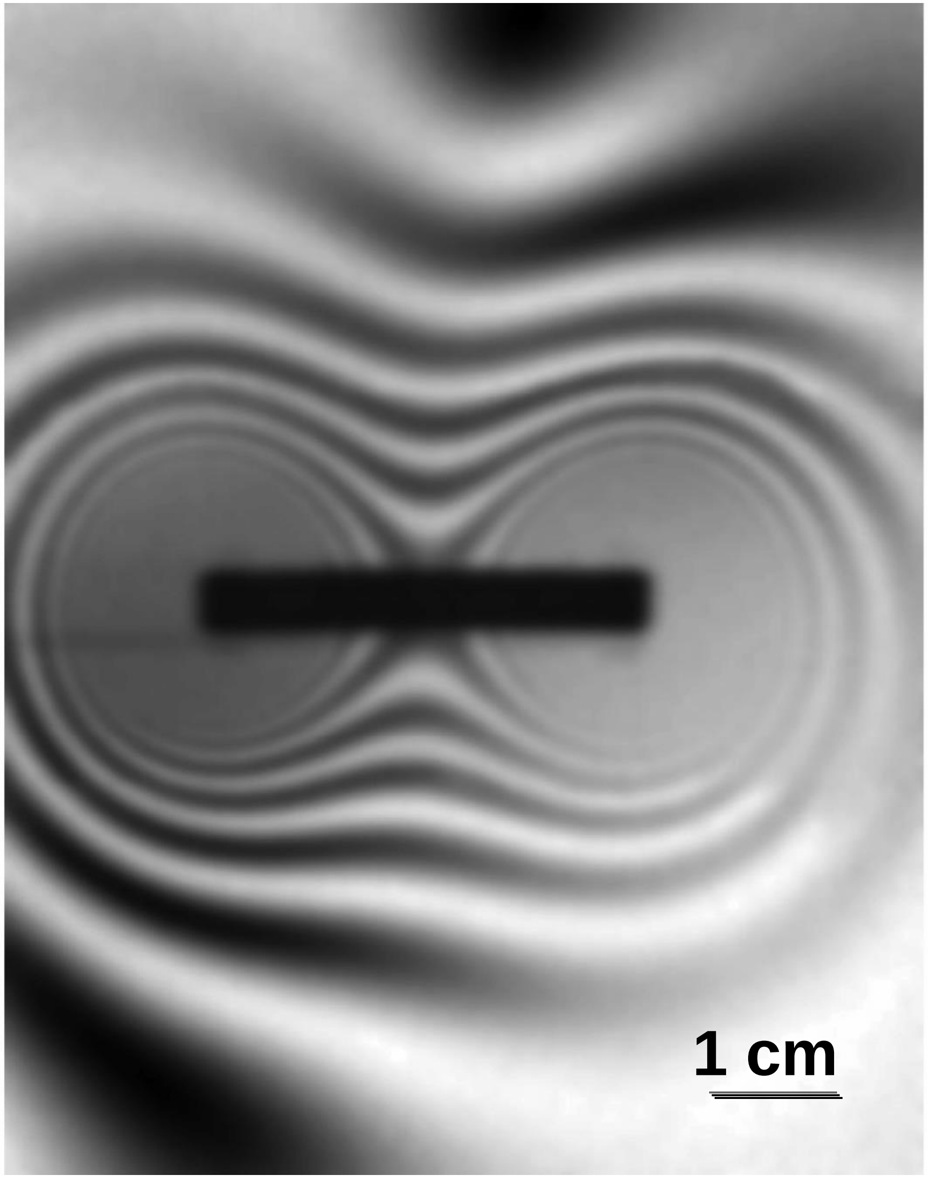
- absorption


- scattering

- magnetic interaction

Imaging with polarized neutrons

Radiography image of a bar magnet taken with polarized neutrons

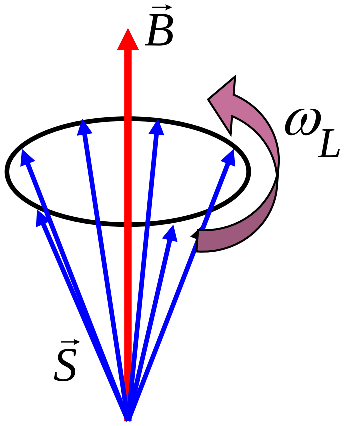


N. Kardjilov, et al,
Nature Physics 4, 399-403, (2008)

Imaging with polarized neutrons

Interactions of neutron spin with magnetic fields

Spin precession arround external magnetic field



Larmor precession with a frequency:

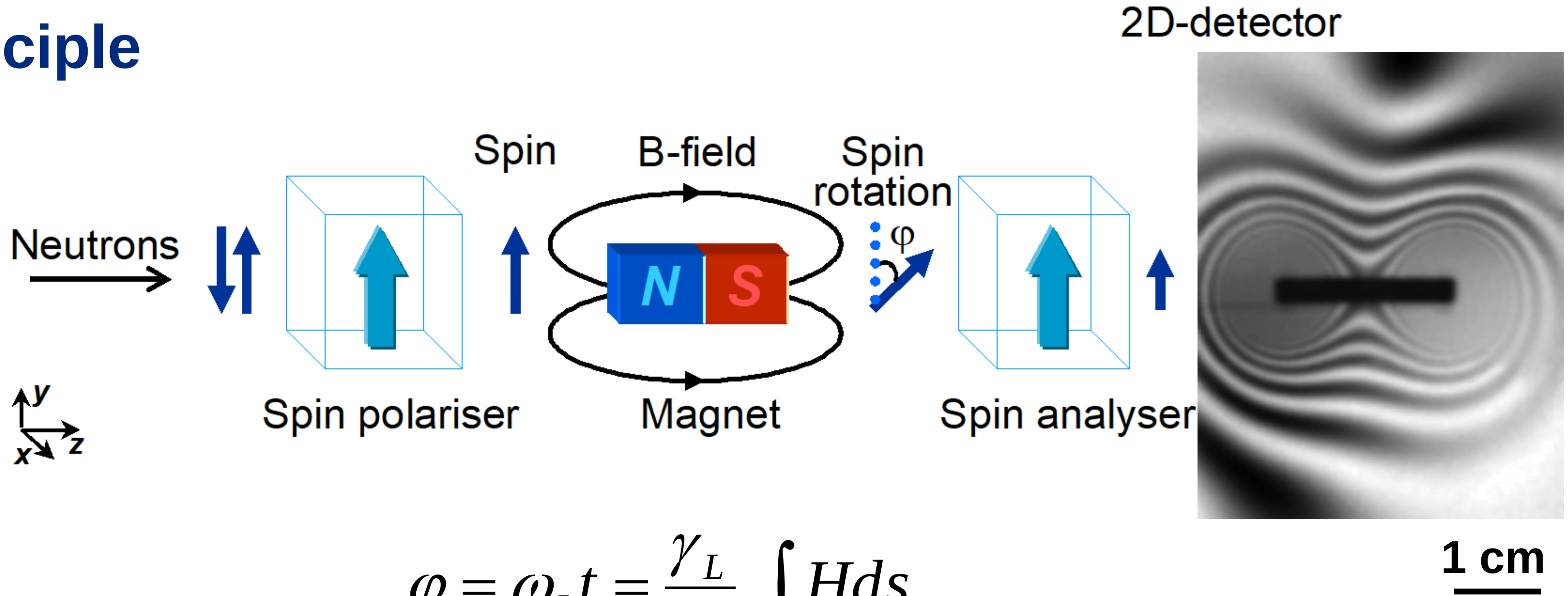
$$\omega_L = \gamma B$$

$$\gamma = 1.83 \cdot 10^8 \frac{rad}{s \cdot T}$$ (gyromagnetic ratio)

The magnetic moment is antiparallel to the internal angular momentum of the neutron described by a spin S with the quantum number s = 1/2.

Imaging with polarized neutrons

Principle



$$\varphi = \omega_L t = \frac{\gamma_L}{v} \int_{path} H ds$$

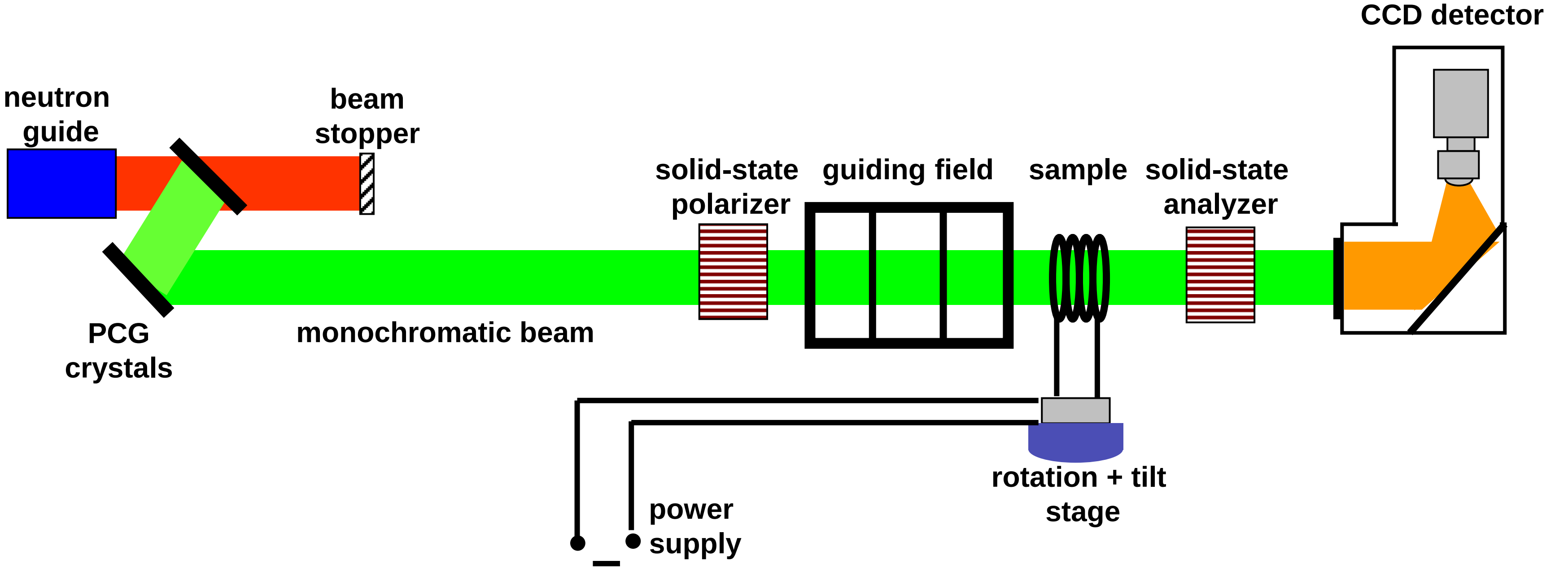
For the imaging setup, a polariser and analyser are used to select a defined neutron polarisation or orientation of the magnetic moment and to convert the precession angle φ of the neutron spin after transmission through the magnetic field or sample to imaging contrast, respectively.

N. Kardjilov, et al, Nature Physics 4, 399-403, (2008)

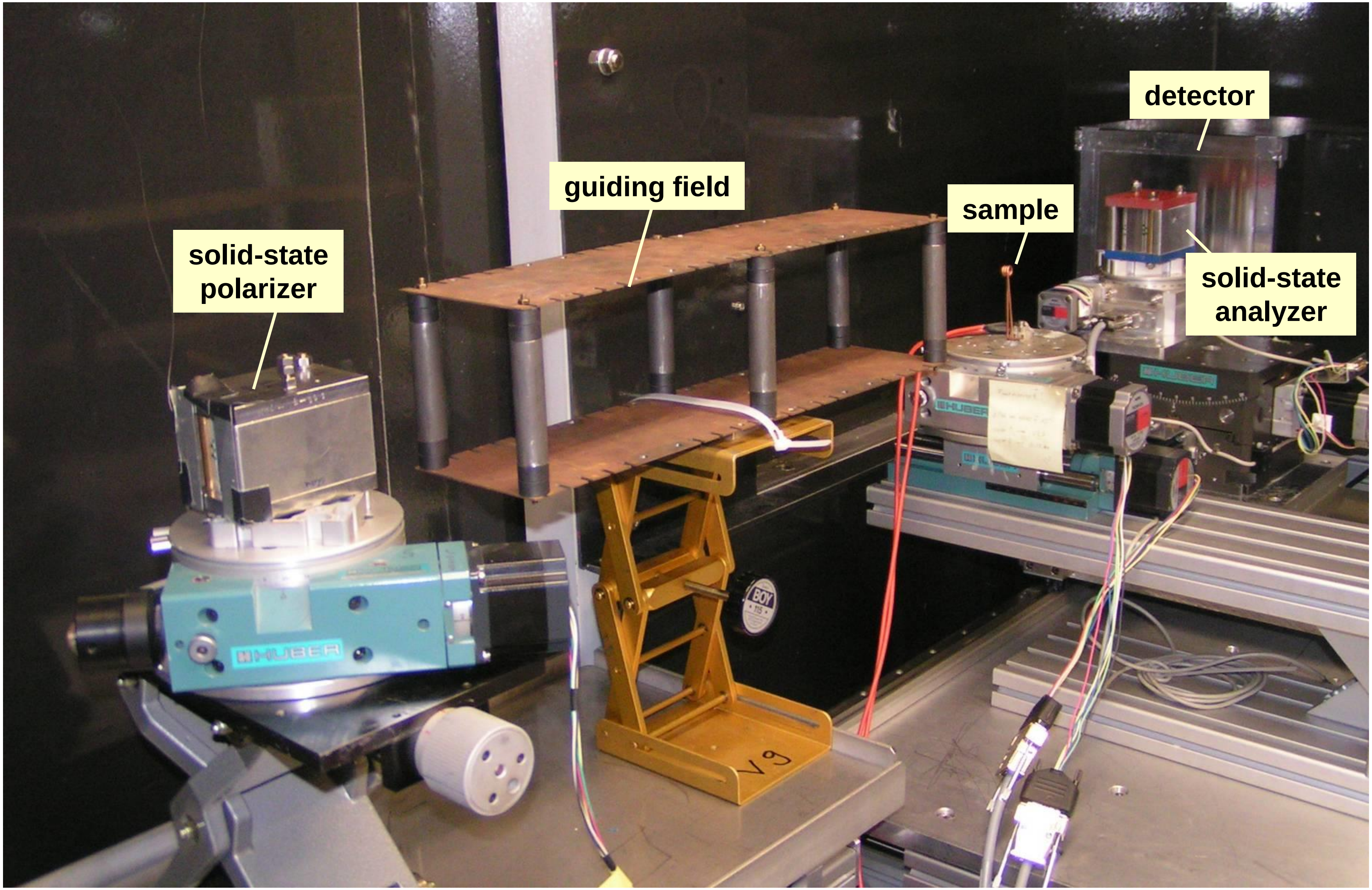
Imaging with polarized neutrons

Example
Instrument: V7 (CONRAD) at HZB, Berlin
Monochromatic beam with wavelength of 4.2 Å
Spatial resolution: 0.2 mm/pixel

Experimental sketch:

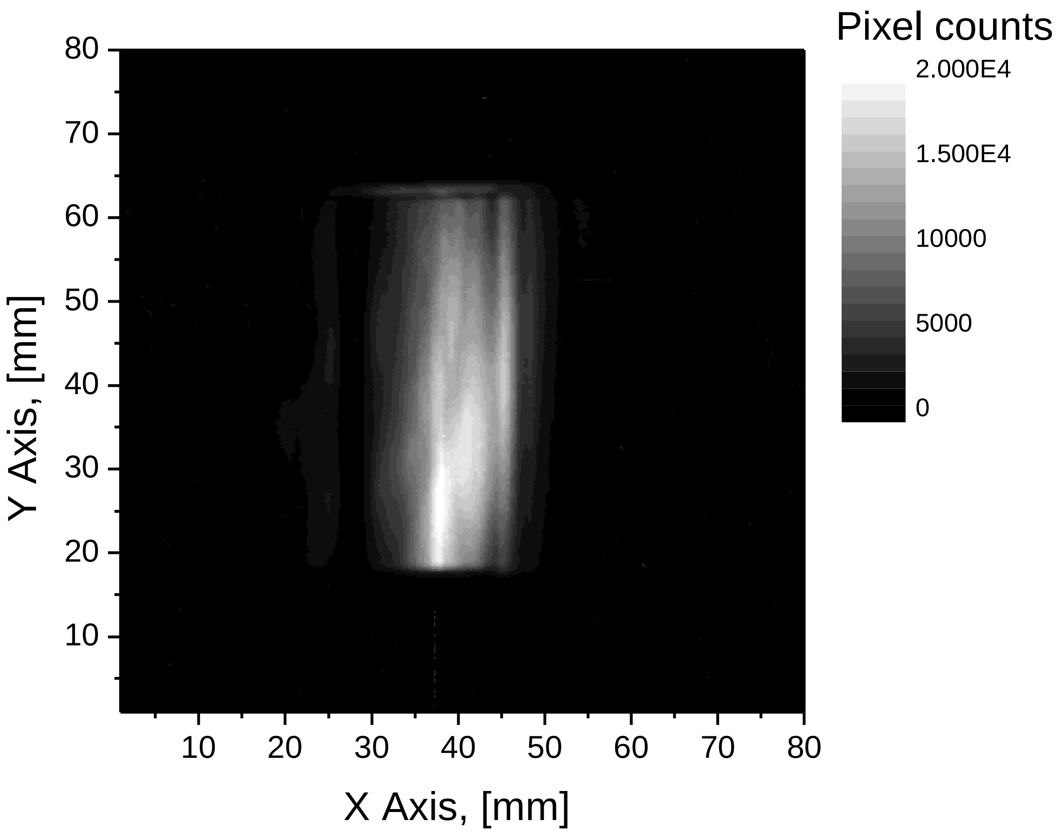


Imaging with polarized neutrons



Imaging with polarized neutrons

Open beam (without sample)



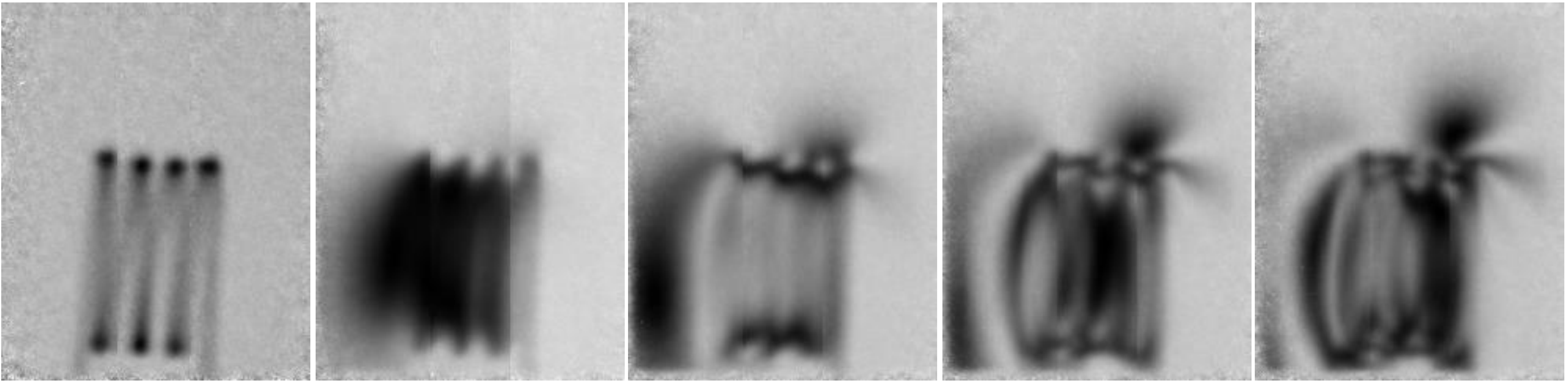
Exposure time: 300 s
Binning: 2x2

Sample

Copper coil
Wire thickness: 2 mm

Imaging with polarized neutrons

Radiography of magnetic field produced by a coper coil applying different currents using polarised neutrons

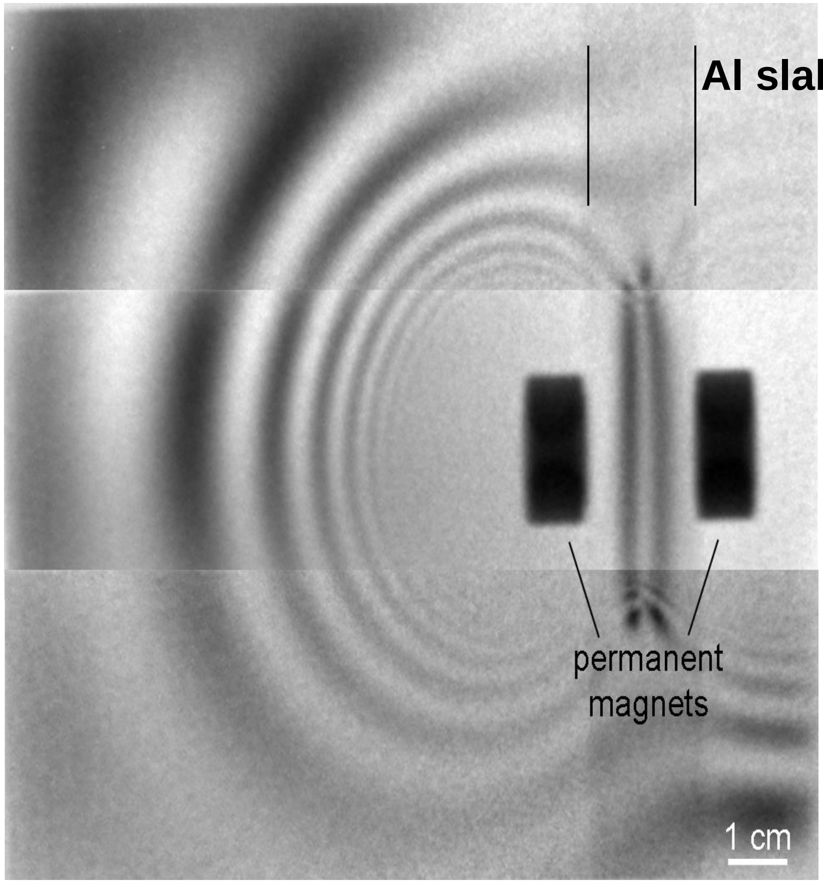


current: 0 Amp | 4 Amp | 8Amp | 12 Amp | 15 Amp

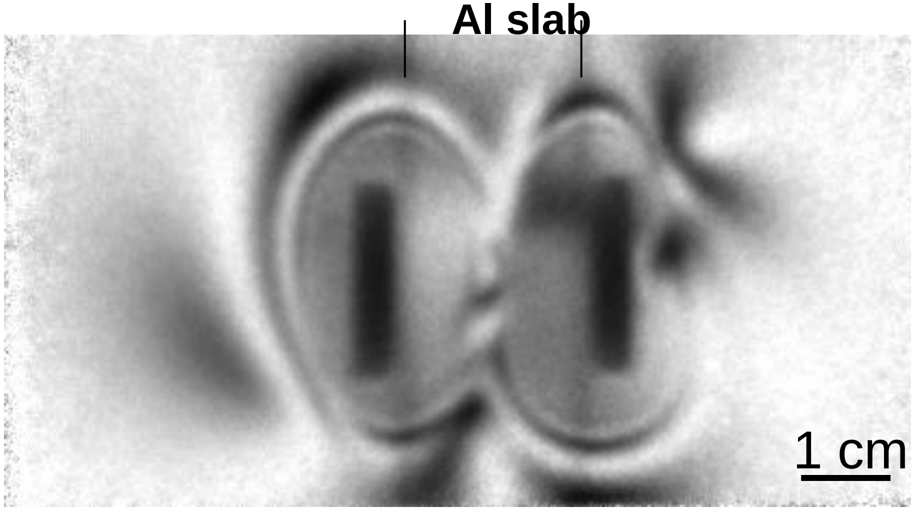
For the imaging setup, a polariser and analyser are used to convert the precession angle φ of the neutron spin after transmission through the magnetic to imaging contrast, respectively.

Imaging with polarized neutrons

Radiography of magnetic field produced by permanent magnets using polarised neutrons



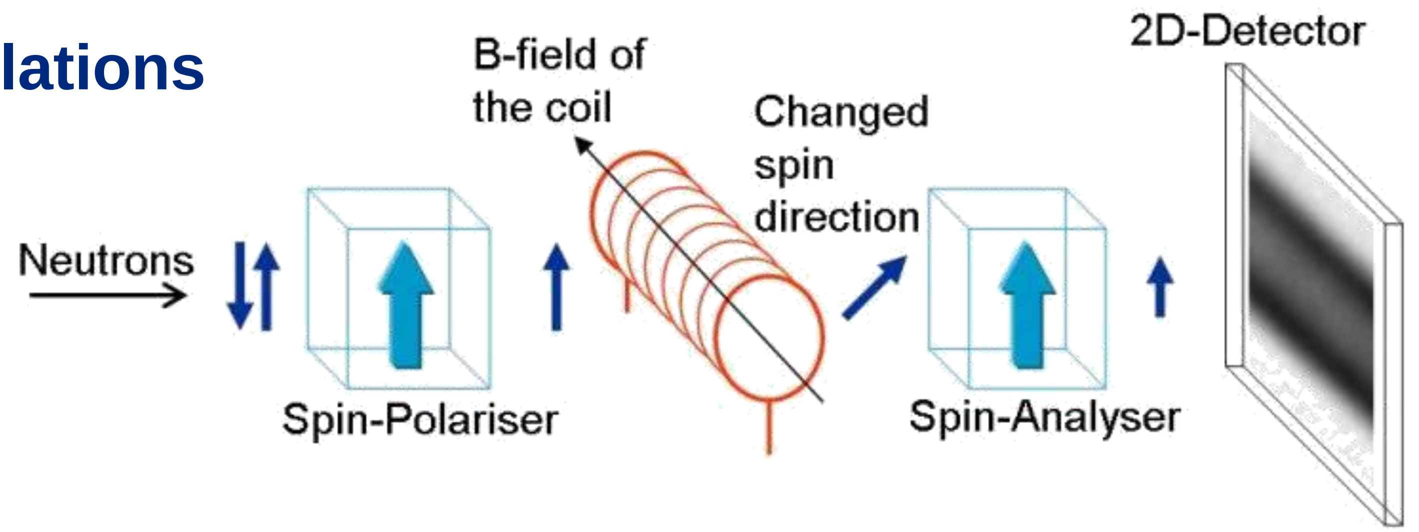
dipole magnets



non-dipole magnets

Imaging with polarized neutrons

Simulations

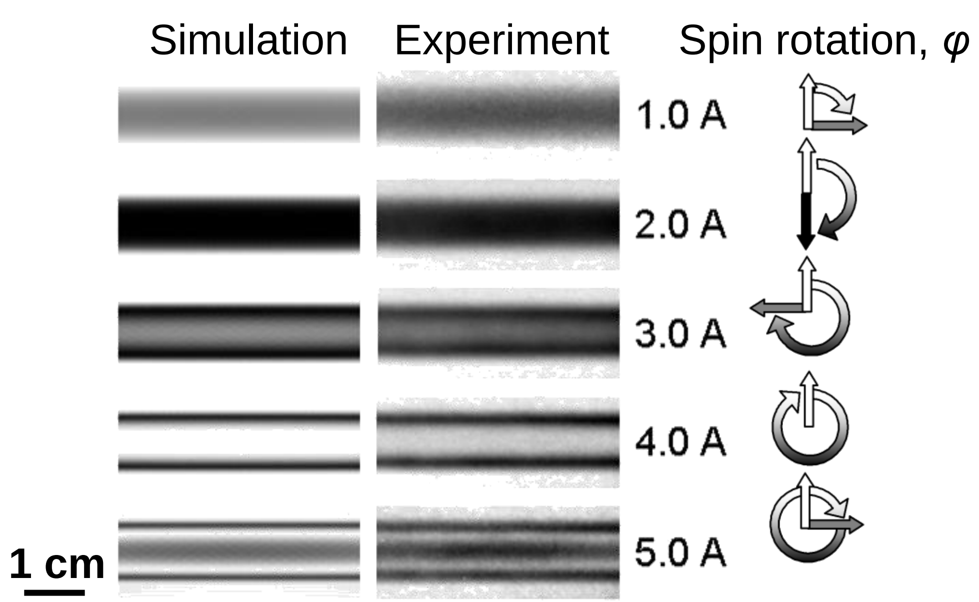


Biot-Savart law

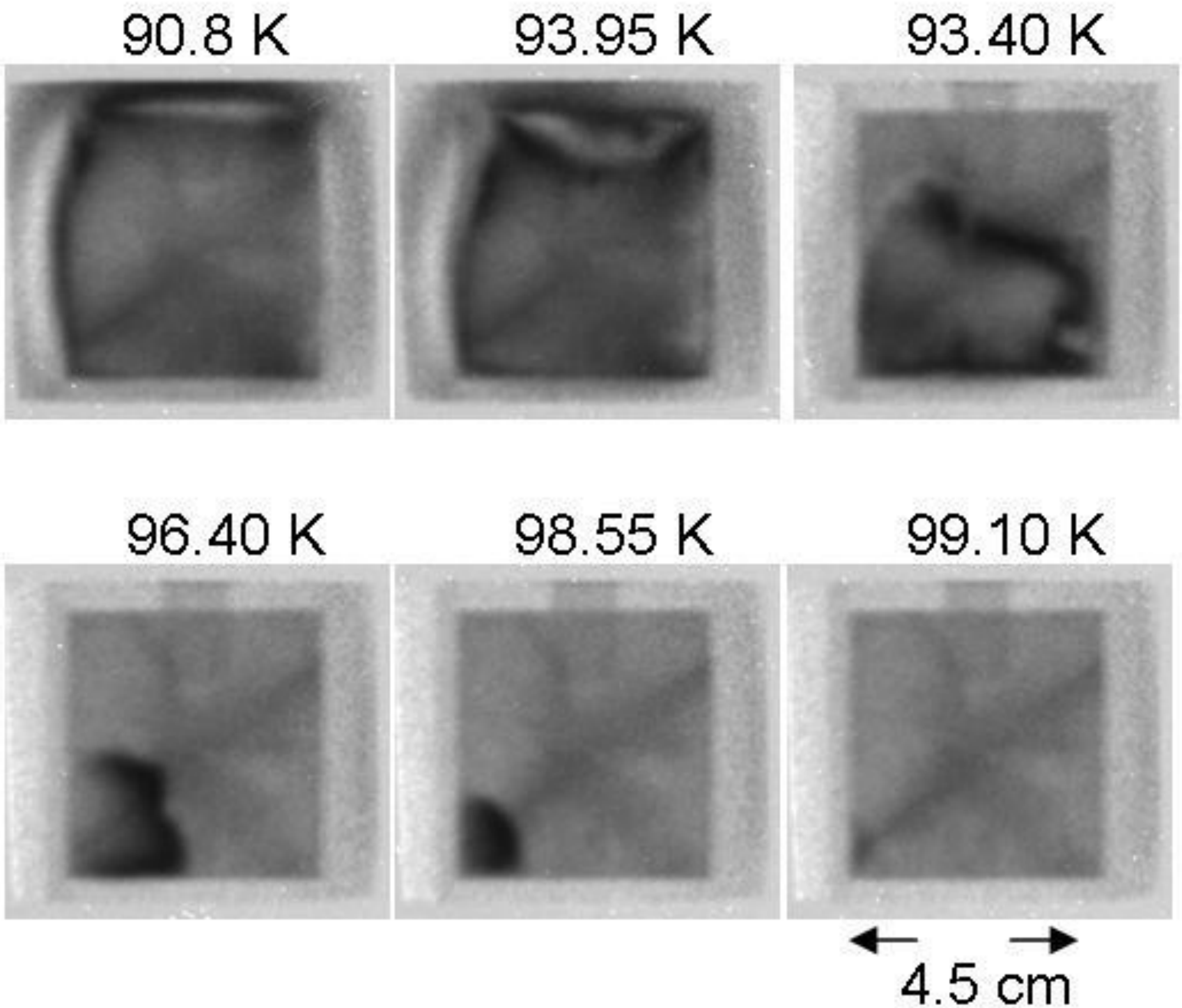
$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \hat{r}}{r^3}$$

$$\phi = \frac{\gamma_L}{v} \int_{path} B\, ds$$

Spin rotation

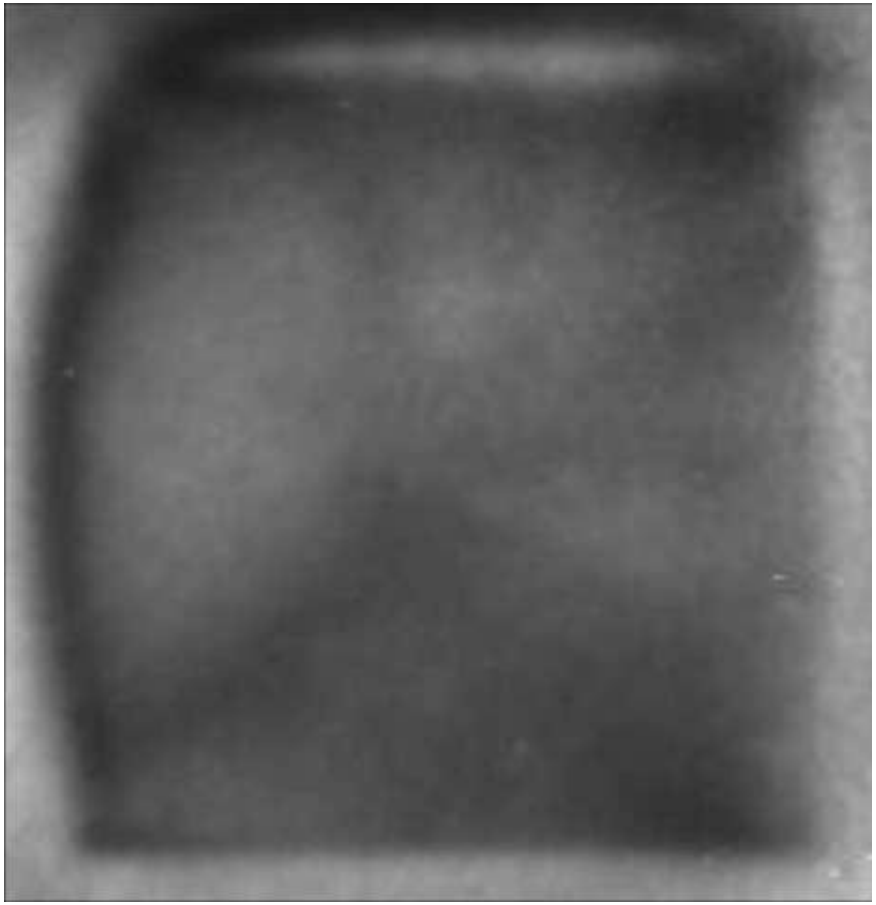


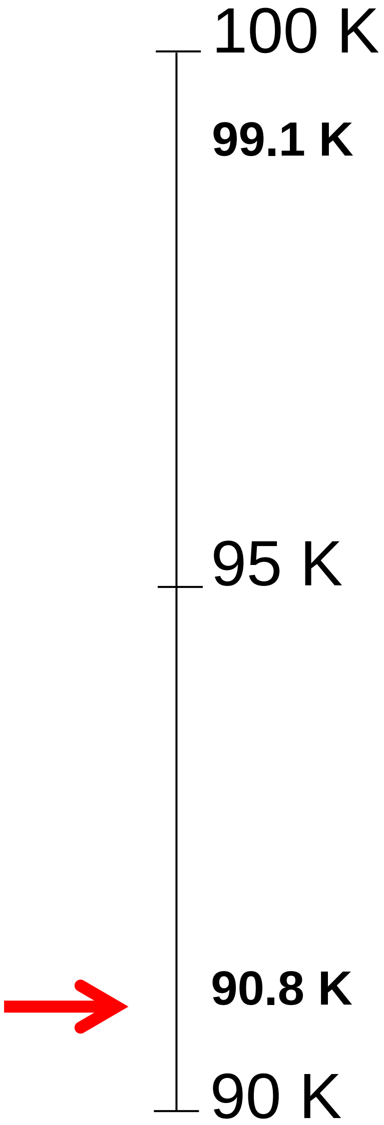
Magnetic Contrast



Flux trapping in a 45x45x12 mm^2 bulk YBCO sample.

Magnetic Contrast

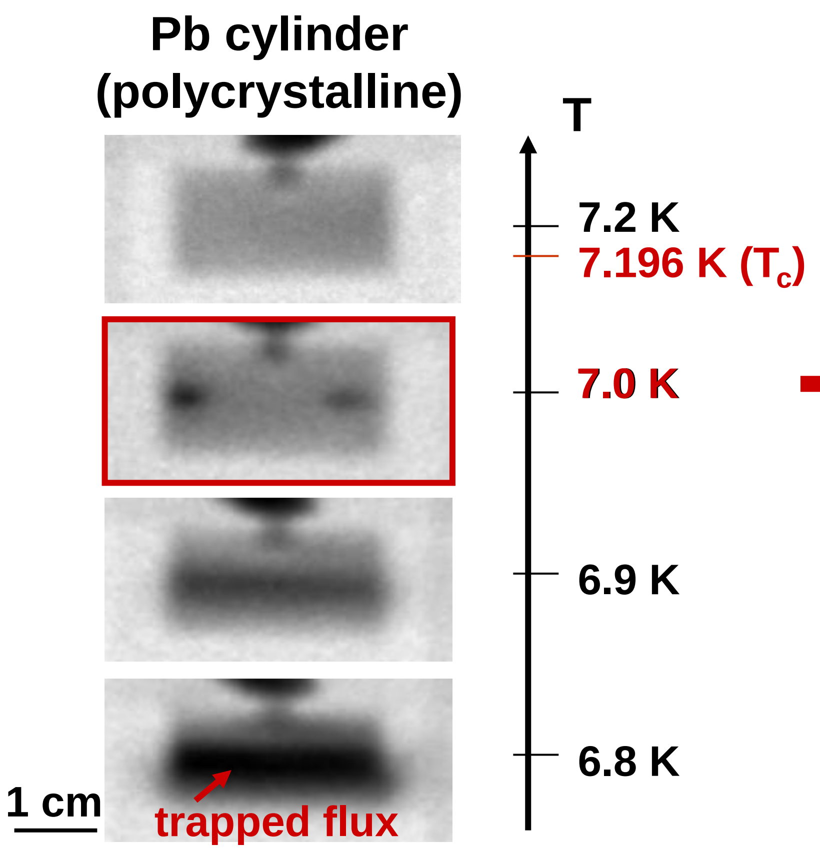


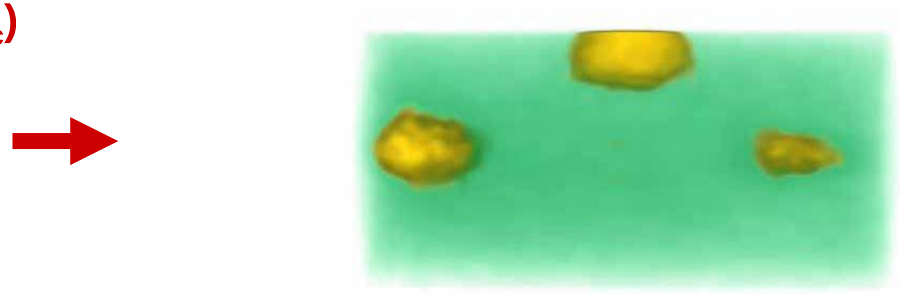


Flux trapping in a 45x45x12 mm^2 bulk YBCO sample.

Magnetic Contrast

Example: Flux pinning

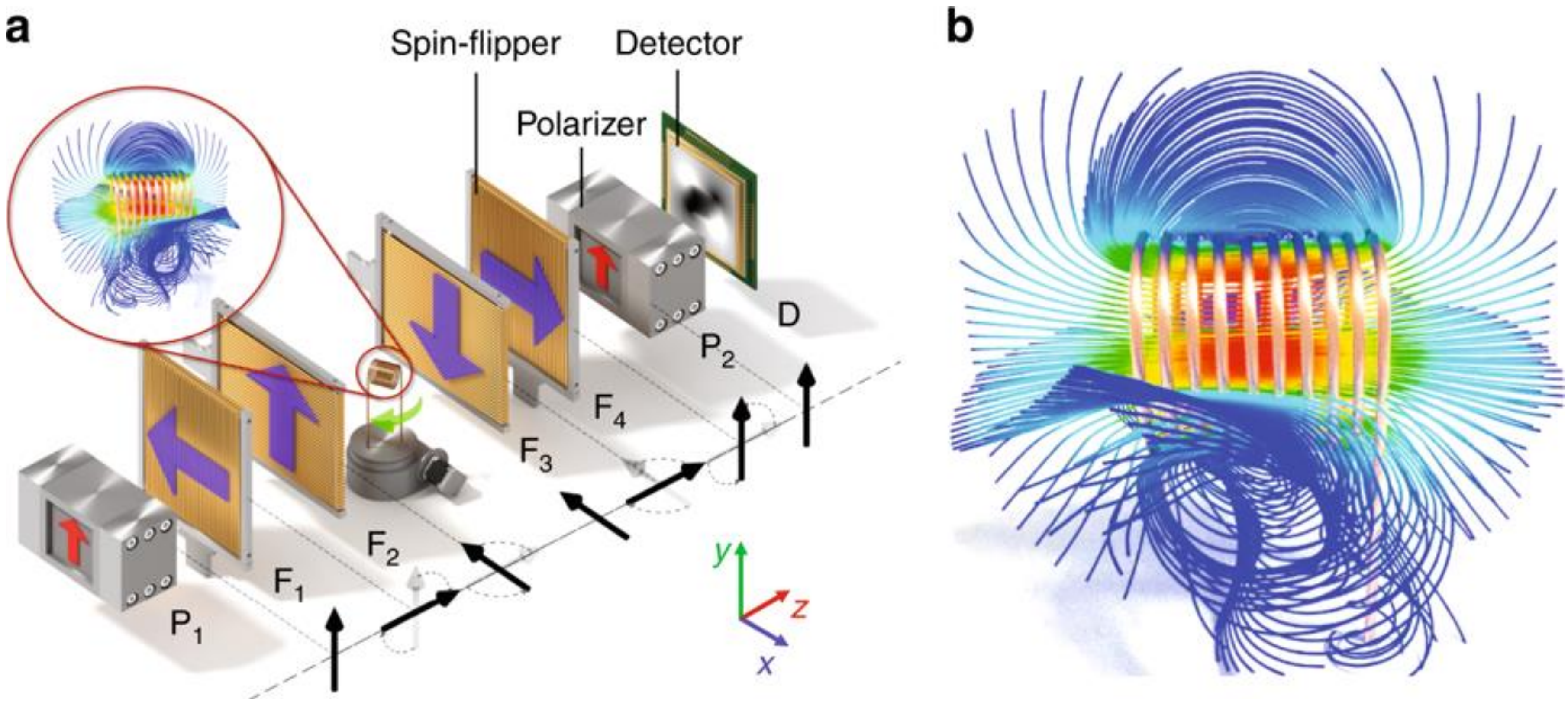




Flux pinning at cooling down below Tc while applying a homogenous magnetic field of 10 mT perpendicular to the beam.

The images were recorded after switching off the magnetic field.

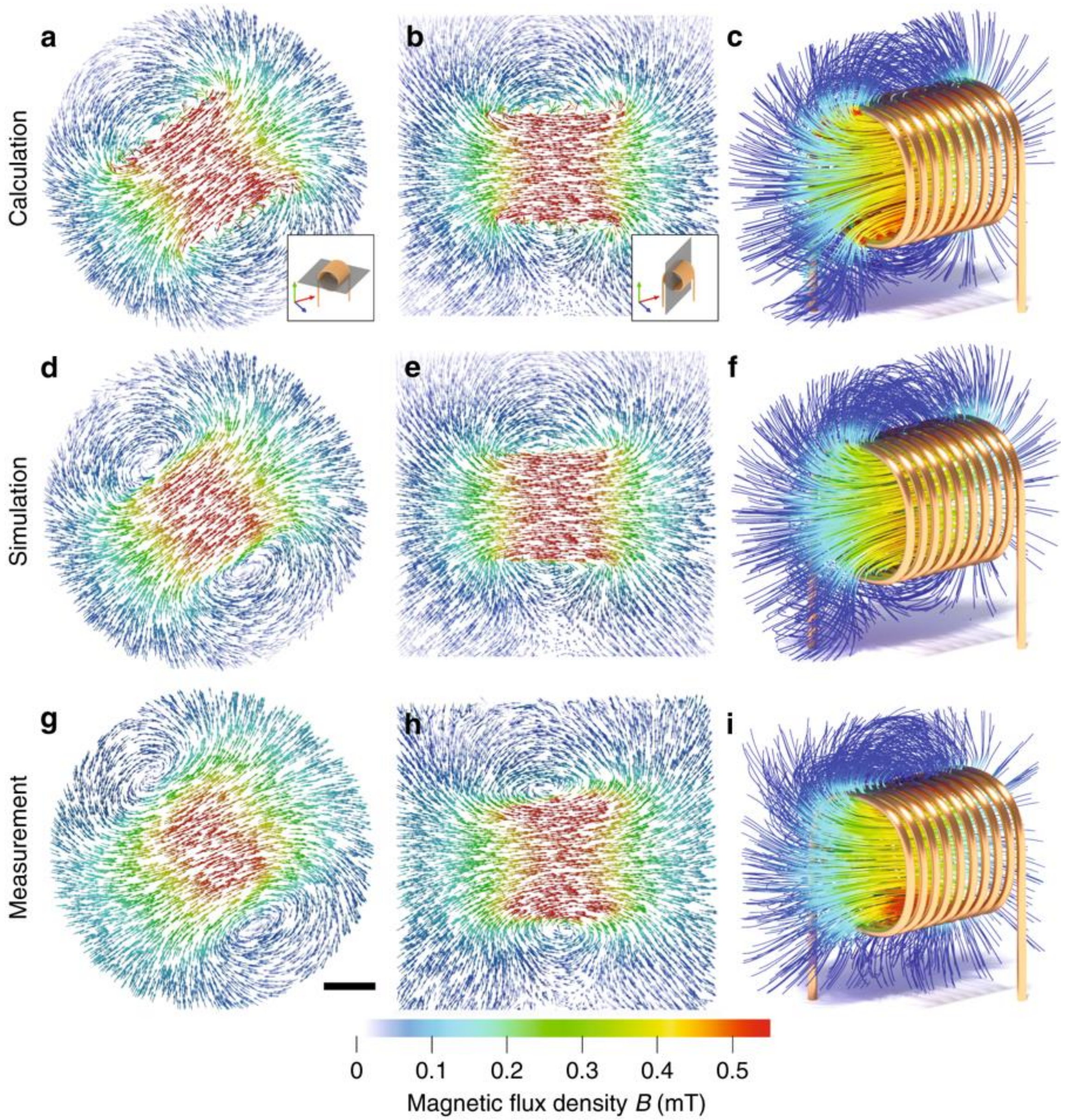
Experimental setup



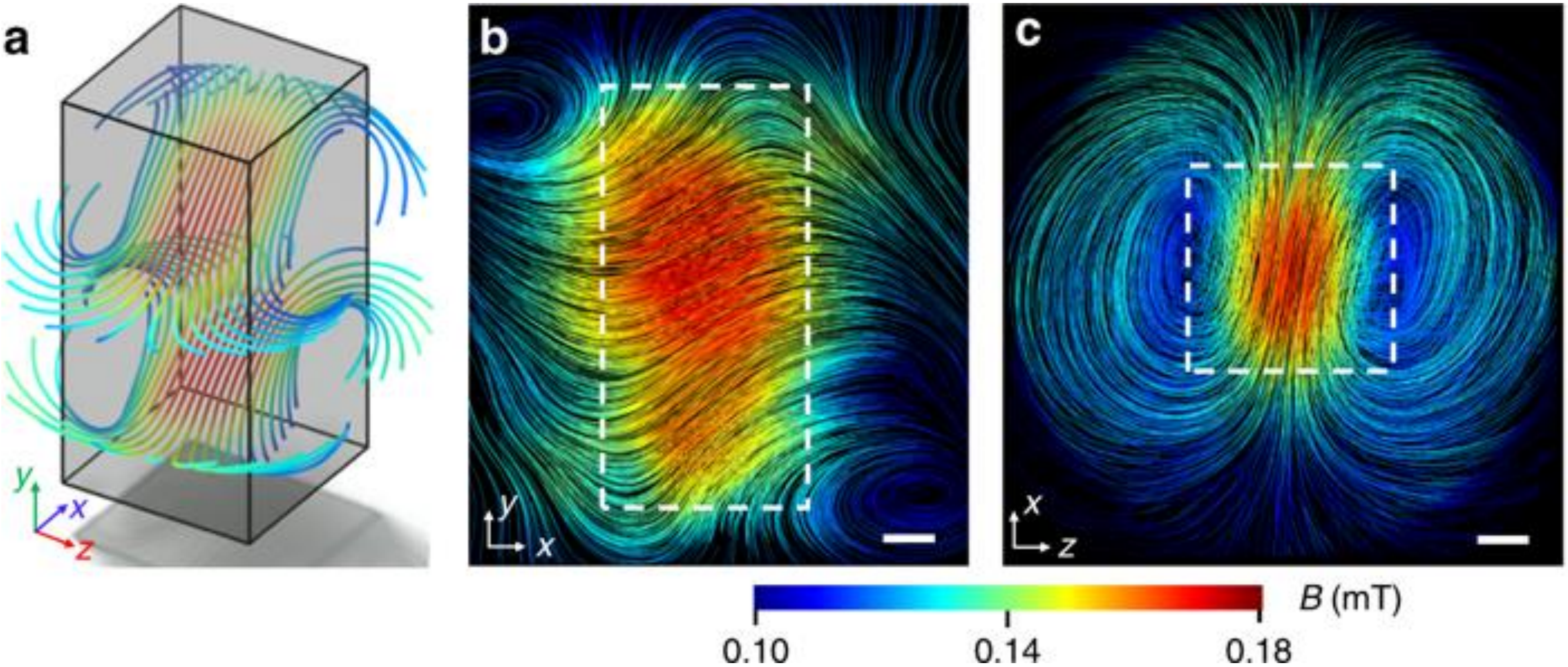
Tensor tomography. **a** Schematic drawing of the setup used for tensor tomography with spin-polarized neutrons, comprising spin polarizers (P), spin flippers (F) and a detector (D). **b** Selected magnetic field lines around an electric coil (calculation)

A. Hilger, et al, Nature Communications 9.1 (2018): 4023

Tensorial reconstruction



Quantitative magnetic tomography



Magnetic vector field inside a superconducting lead sample measured at $T = 4.3$ K. **a** Some selected magnetic field lines show the location of the magnetic field inside the sample indicated by the cuboid. **b** Magnetic field lines in a selected *xy* plane (silhouette of the lead sample marked by dotted lines). Scale bar, 5 mm. **c** Magnetic field lines in a selected *xz* plane. Scale bar, 5 mm.

A. Hilger, et al, Nature Communications 9.1 (2018): 4023

Summary

Neutron Imaging (NI)

- is a technology to produce visible information of objects and structures by using beams of free neutrons
- due to the high penetration power of neutrons for most of the observed materials also inner features can be visualized
- NI is therefore a suitable tool for non-destructive testing and for applied research

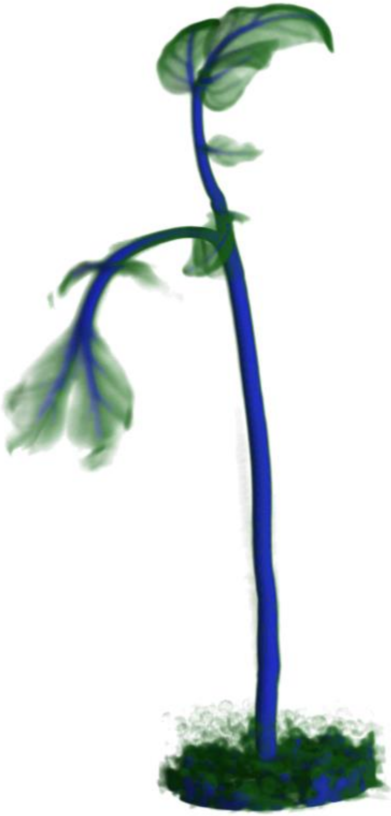
Summary

ADVANTAGES

- no charge: often deeper penetration
- magnetic moment: magnetic interaction with nuclei → polarized neutrons
- high sensitivity for light elements
- different isotopes can be distinguished (D:H, B-10:B-11, Li-6: Li-7, U-235:U-238)
- energy selection using time-of-flight (at pulsed sources)

DISADVANTAGES

- neutron intensity limited
- no direct detection – a secondary process is needed (limiting spatial resolution)
- no charge: no focusing and guiding by el.-magnetic fields possible
- risks of samples activation



Thank you !

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